

NAS3-20643  
October 30, 1981  
R81AEG709

# ENERGY EFFICIENT ENGINE COMPONENT DEVELOPMENT & INTEGRATION PROGRAM

## SEMIANNUAL REPORT No. 7

April 1, 1981 - September 30, 1981



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(NASA-CR-170034) ENERGY EFFICIENT ENGINE  
COMPONENT DEVELOPMENT AND INTEGRATION  
PROGRAM Semiannual Report, 1 Apr. - 30 Sep.  
1981 (General Electric Co.) 338 p  
HC A15/MF A01

N85-10990

Unclas  
CSCL 21E G3/07 24793

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## FOREWORD

This contract effort is being conducted by NASA as part of the Energy Efficient Engine project. It is managed by the NASA-Lewis Research Center, with Carl C. Ciepluch serving as the NASA Project Manager and Peter G. Batterton serving as the NASA Assistant Project Manager responsible for this contract.

This semiannual report covers the work performed under Contract NAS3-20643 for the period of April 1, 1981 through September 30, 1981. It is published for technical information only and does not necessarily represent recommendations, conclusions, or the approval of NASA. The data generated under this contract are being disseminated within the U.S. in advance of general publication in order to accelerate domestic technology transfer. Since all data reported herein are preliminary information, they should not be published by the recipients prior to general publication of the data by either the Contractor or NASA.

Selected portions of the data (that is, those data pertaining to specific component design details) are considered to have significant early commercial potential. As such, these data are designated as Category 2 Data under NASA FEDD (For Early Domestic Dissemination) policy and are restricted from foreign dissemination for at least 2 years from the date of this report. Category 2 data may be duplicated and used by the recipient with the expressed limitation that the data will not be published or released to foreign parties during this period without the expressed permission of the General Electric Company and appropriate export licenses. Release of these Category 2 data to other domestic parties shall only be made subject to the limitations that all recipients must agree, prior to receiving these data, to abide by the limitations of the FEDD legend on the cover of this report.

## INTRODUCTION

This is the seventh semiannual report under Contract NAS3-20643 - NASA Energy Efficient Engine (E<sup>3</sup>) Component Development and Integration Program. The report covers the period April 1, 1981 through September 30, 1981.

The program objective is the development of technology that will improve the energy efficiency of propulsion systems for subsonic commercial aircraft of the late 1980's or early 1990's. The following goals have been established.

- Fuel Consumption

A reduction in Flight Propulsion System (FPS) cruise installed sfc of at least 12% compared to the reference CF6-50C engine. (Cruise is defined as Mach 0.8 and 35,000 feet on a standard day at maximum cruise power without bleed or power extraction.)

- Direct Operation Cost (DOC)

A DOC reduction of at least 5% based on advanced aircraft with E<sup>3</sup> compared to scaled CF6-50C.

- Noise

FAR-Part 36 (as amended July 1978) with provision for engine growth corresponding to future engine application.

- Emissions

EPA new engine standards January 1981.

CO	(lb per 1000 lb thrust-hr per cycle)	3.0
HC	(lb per 1000 lb thrust-hr per cycle)	0.5
NO <sub>x</sub>	(lb per 1000 lb thrust-hr per cycle)	3.0
SMOKE	(SAE-SN)	20.0

General Electric is projecting a reduction of 14.4% in cruise installed sfc (0.572 versus 0.668 for the CF6-50C) and a DOC reduction in excess of the 5% goal. Noise and emissions projections are consistent with the established goals.

In addition to the foregoing, growth of the FPS is being considered from the outset. A minimum installed-thrust level of 36,500 lbf has been established for the FPS at takeoff. A planned growth of 20% maximum climb thrust

over the baseline rating is desired without compromise of the foregoing goals. Components of the engine are to be designed with consideration for growth and the competitiveness of the initial engine.

Commercial transport engine requirements will be factored into the development effort, as appropriate, with the objectives of (1) making the resulting technology useful for subsequent commercial application and (2) normalizing the risk of any future commercial developments.

Four major technical tasks have been established for the E<sup>3</sup> program. Task 1 addresses the design and evaluation of the E<sup>3</sup> Flight Propulsion System; this propulsion system is designed to meet the requirements for commercial service and includes a flight nacelle. The Task 1 results will establish the requirements for the experimental test hardware including the components, core, and integrated core/low spool. Task 2 consists of the design, fabrication, and testing of the components and includes supporting technology efforts. These supporting technology efforts are to be performed where required to provide verification of advanced concepts included in the propulsion system design. In addition, more advanced technologies that are not specifically included in the propulsion system design but which provide the potential for further performance improvements are also to be explored. Task 3 involves the design, fabrication, and test evaluation of the core engine consisting of the compressor, combustor, and high pressure turbine. Integration of the core with the low-spool components and test evaluation of the integrated core/low spool comprise Task 4. At the conclusion of the program, the latest performance of the experimental hardware (integrated core/low spool and concurrent core and component efforts) will be factored into a final propulsion system/aircraft evaluation (as part of continual, ongoing evaluations in Task 1) to determine achievable performance as compared to program goals. Task 5 is a nontechnical task that encompasses the Project/Program Management and Control System established for the contract. The Master Program/Project Schedule is shown in Figure 1.

This report provides a review of the work accomplished during the first 45 months of the E<sup>3</sup> contract, with emphasis on accomplishments during the

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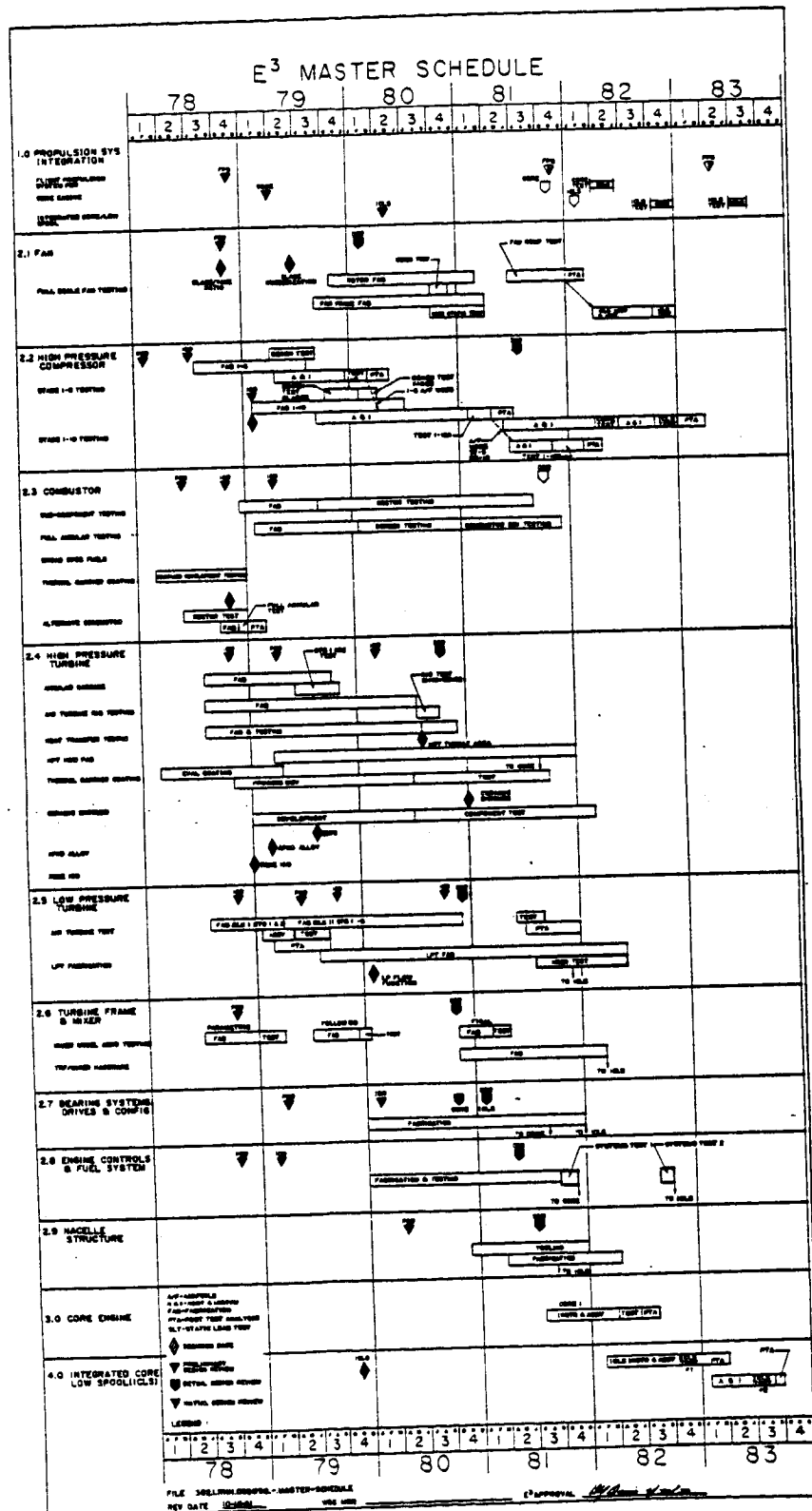


Figure 1. Master Program Schedule.

past 6 months. It is a progress report, and the data contained herein are subject to change during the remaining period of performance. The report is responsive to and consistent with the requirements of the Statement of Work.

#### Summary of Progress

The first 60 days under contract were devoted to planning the program. This period culminated in the Work Plan, the basis of which is the Work Break-down Structures (WBS) established in accordance with the elements contained in the contract Statement of Work. The WBS is presented in Table I in an abbreviated form. Program and design highlights, progress, and overall perspective are reported herein for the systems and components. All WBS items in which work was performed during this report period are documented. Some of the highlights during this report period are

- All core engine hardware drawings have been issued.
- The fan rig was instrumented, assembled, and installed. Testing has been started.
- Tests were completed on the 10A compressor rig. Efficiency exceeded the goal for this test. Blading was selected for the 10B rig and for the core engine. Assembly of the 10B compressor rig is underway.
- Testing of the full annular development combustor has been completed. Testing of the sector combustor has been completed except altitude relight tests. Preparations are underway to rig test the core engine combustor. Based on results to date, performance and emissions goals are expected to be met in the core combustor.
- The Block II two-stage low pressure turbine rig was assembled and tested. Efficiency was 3/4 point better than the Block I two-stage rig. The Block II five-stage LPT rig was assembled and has completed testing. Preliminary results are that efficiency exceeded the ICLS goal by 0.2 points.
- Phase III scale-model mixer testing was completed. The sfc gain due to mixing is 2% for the ICLS mixer and 2.6% for the FPS mixer. The goal is 3.1% for FPS.
- All component detail design reviews have been presented except the combustor which will be in October 1981.

Table I. Work Breakdown Structure.

- 1.0 Task 1 - Propulsion System Analysis, Design, and Integration
  - 1.1 Propulsion System
  - 1.2 Cycle and Performance
  - 1.3 Materials and Processes
  - 1.4 Acoustic Development
  - 1.5 Propulsion System Aircraft Integration and Development
  - 1.6 Benefit/Cost Study
- 2.0 Task 2 - Component Analysis, Design, and Development
  - 2.1 Fan
  - 2.2 Compressor
  - 2.3 Combustor
  - 2.4 High Pressure Turbine
  - 2.5 Low Pressure Turbine
  - 2.6 Turbine Frame and Mixer
  - 2.7 Bearings, Systems, Drives, and Configuration
  - 2.8 Engine Controls and Fuel System
  - 2.9 Nacelle Structure
- 3.0 Task 3 - Core Testing
  - 3.1 Initial Core Build
  - 3.2 Second Core Build
  - 3.3 Core Posttest Analysis
- 4.0 Task 4 - Integrated Core/Low Spool (ICLS) Testing
  - 4.1 ICLS Engineering and Analysis
  - 4.2 ICLS Fabrication
  - 4.3 ICLS Assembly and Instrumentation
  - 4.4 ICLS Test Facilities Engineering
  - 4.5 ICLS Testing
  - 4.6 ICLS Posttest Analysis
  - 4.7 Follow-on ICLS Testing
- 5.0 Task 5 - Management
  - 5.1 Project Management
  - 5.2 Configuration Management
  - 5.3 Reporting

- The decision was made to start with the combustor pilot dome only. This was possible because of better-than-projected compressor and turbine performance. Starting on the pilot dome substantially improves emissions and avoids compromises in the combustor.
- A major activity has been expediting core engine hardware manufacture. The critical hardware are compressor Stage 7, 8, and 98 vane segments, HPT Stage 1 and 2 nozzles, and HPT Stage 1 blades.
- Core engine hardware is being accumulated for the centerline stack operation.
- WBS 1.6, a benefit/cost study to identify high potential technology areas beyond FPS, has been started.

A continuing problem has been experienced with regard to long lead times for procurement of hardware, with subsequent impact on program schedules. Schedule adjustments were made during this reporting period to accommodate hardware slips and are discussed individually in the applicable WBS sections.

1.0 TASK 1 - PROPULSION SYSTEM ANALYSIS, DESIGN AND INTEGRATION

Overall Objectives

The primary objectives of this task are to provide the preliminary design of the flight propulsion system (FPS) and to evaluate the progress of the FPS to ensure that NASA program goals are being met. In addition, periodic updates and reassessments of the FPS will be conducted to ensure that FPS projections contain the most current information available from the component technology development program. Periodic preliminary design reviews (PDR) based on material and data developed under this task will be conducted to provide program status information.

As part of this task, cycle decks and performance projections for the FPS will be developed and kept current. All system integration efforts are conducted through this task, such as FPS layouts, overall assembly drawings, parts lists, and design change monitoring. All aspects of the system, including acoustic evaluation, aircraft integration, engine dynamics, reliability, life management, and fan and compressor compatibility, are coordinated and results incorporated under Task 1. Other results are the evaluation of the system benefits of the FPS and a determination as to whether direct operating cost and fuel savings goals are being met. Another objective of this task is to conduct a supporting material technology program and to provide the reviews of the material selected for use in the program.

Task 1 also has the objective of providing preliminary Core Engine and Integrated Core/Low Spool (ICLS) designs and appropriate efforts to integrate the designs and to ensure that hardware support is provided, as appropriate, for Core/ICLS testing. In addition, Core and ICLS PDR and Detail Design Reviews (DDR) will be conducted based on the data generated during the task.

Development Approach

Evaluation and updates of the FPS will be accomplished by blending information that becomes available from the preliminary design phases of the FPS, Core, and ICLS with information that becomes available from Tasks 2, 3, and 4 as the program proceeds.

Initially, layouts and system characteristics were developed from the proposal FPS and any subsequent modifications that occurred before and after the first FPS PDR. Information from the supporting efforts under the Propulsion System Design effort will be combined with that from the other Task 1 efforts, such as aircraft integration and evaluation, and acoustic studies to update the FPS status.

As changes and new estimates of component and system performance become available, new layouts and system evaluation updates will be generated for the appropriate FPS PDR.

Continual monitoring of the Core and ICLS design and hardware, along with implementation of the system integration responsibility, will ensure that accurate knowledge of the FPS configurations and characteristics is always available. It also ensures that changes to the Core and ICLS that could adversely affect the performance of the FPS will be known and that action will be taken, when necessary, to prevent FPS degradation.

As the program proceeds, all important aspects of the Core and ICLS performance and characteristics will be translated into meaningful information for FPS PDR's. Final program results and a final FPS projection will be obtained and communicated in this manner.

### Flight Propulsion System Description

General Electric's proposed E<sup>3</sup> Flight Propulsion System is a high-bypass, dual-rotor, axial-flow turbofan with a fan pressure ratio of 1.65 and an overall pressure ratio of 38 at the maximum climb power matching point. At maximum cruise, the bypass ratio is approximately 7. For the sea level takeoff (SLTO) maximum thrust rating of 36,500 pounds, the combustion temperature for the FPS is projected to be 2450° F. A symmetrical nacelle with a long-duct, mixed-flow nozzle completes the installation. A cross section of the proposed installed engine is shown in Figure 1.1-1.

The major engine components are the fan rotor and stator module; the core engine, consisting of the compressor, combustor, and two-stage turbine; the low pressure turbine module, mounting provisions, and exhaust mixer; and the core-mounted accessories.

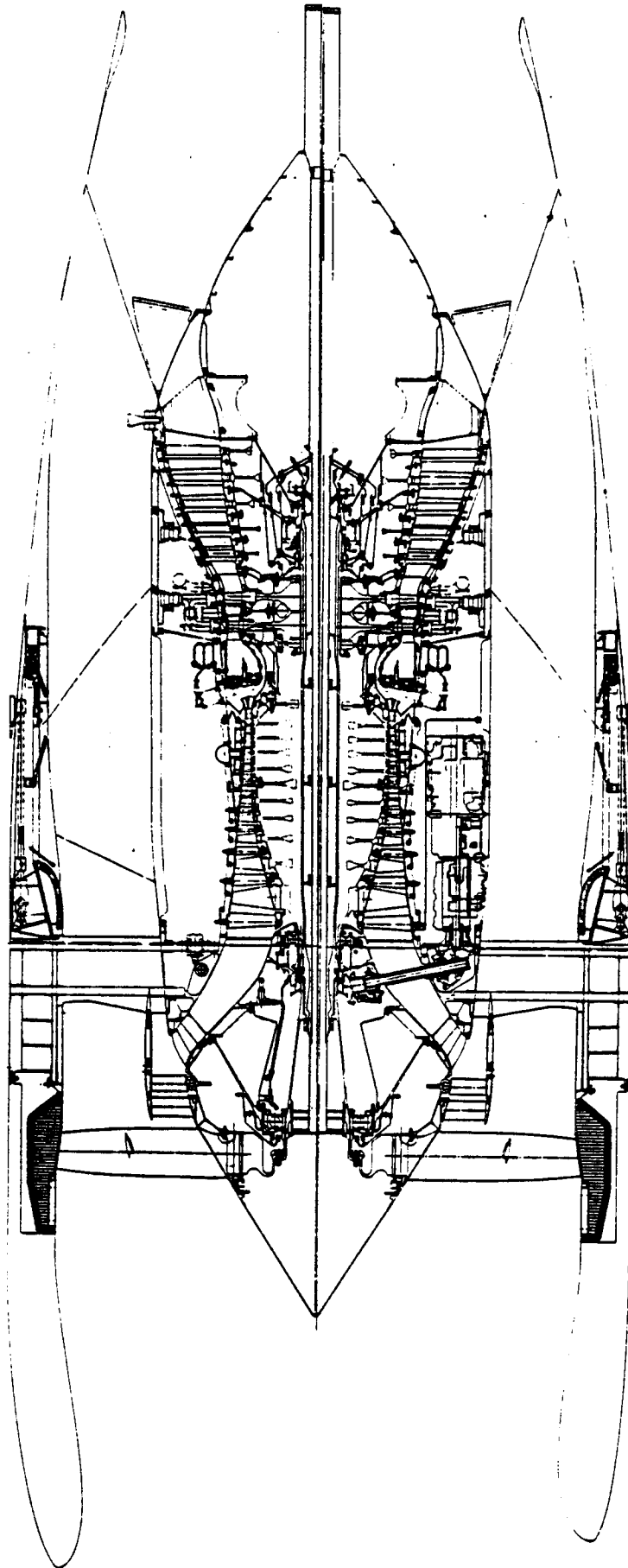


Figure 1.1-1.  $E^3$  Propulsion System.

The fan rotor, consisting of a 32-blade fan stage and a 56-blade quarter stage for core compressor supercharging, is driven by a five-stage turbine. Titanium was utilized for blading to provide foreign object damage (FOD) ruggedness. The quarter stage provides approximately 1.7 times as much air as the core requires. The excess air is bypassed into the fan exhaust duct, providing automatic flow matching and FOD separation. The fan turbine uses tip shrouds and blade/vane root overlap to reduce leakage and aerodynamic losses. A circumferentially continuous fan turbine casing (coupled with modulated casing cooling) provides active clearance control. Increased blade numbers are used in the next-to-last fan turbine stage to raise puretone frequencies and reduce perceived noise.

The fan frame is integrated with the fan outer duct and nacelle to provide a stiff, lightweight structure. The outer frame and duct are constructed of graphite-epoxy materials; the inner frame is aluminum. Containment for the fan blades is provided by a hybrid system of steel backed up by wrapped Kevlar.

The core compressor has 10 stages of rugged, low-aspect-ratio blading to reduce stress levels and erosion, and it provides a compression ratio of 23 at the maximum-climb matching point. The last five stages of compressor have active clearance control and a separate aft casing support to improve running clearances. There are five stages of variable-geometry vanes to improve matching and efficiency at off-design conditions, and seventh-stage bleed is available for starting.

The combustor is a double-annular design for low emissions and is patterned after the combustor developed under a NASA low-emissions combustor development program based on the CF6 engine. A shingle liner configuration is employed; the hot shingle liner is nonstructural (except for cooling and pressure loads) while the cool outer liner is used for all combustor support and positioning functions. The outer combustor nozzles are used for low-thrust conditions; as thrust is increased, the inner set of main nozzles begins to function.

A two-stage turbine completes the core engine configuration. Advanced directionally solidified René 150 is used for the Stage 1 and 2 blading and

the Stage 2 vanes. The Stage 1 vanes are constructed of an oxide-dispersion-solidified (ODS) material that has provided good service in other high-temperature nozzle applications. Both turbine disks are boltless designs with smooth side plates for low windage losses. The cooling-air circuits have been configured to provide the coolest air possible with no excess pressure losses or leakage for increased thermodynamic efficiency. The cooling circuit for the Stage 1 blades also provides a cooling layer over the compressor and turbine interconnecting shaft. Active clearance control over the turbine is achieved with an engine control function that selectively cools the support rings of the shrouds, permitting blade running clearance to be changed thermally under transient and steady-state conditions to permit minimum blade-to-shroud average clearances.

A double-wall design is used in the aft hot sump to ensure that the inner sump is adequately cooled. Two separate sources of cooling air purge the outer and inner walls of the aft sump to prevent any inadvertent overheating. A center vent system exhausts the sump pressurization air back through the exhaust cone to the engine nozzle region.

The engine accessory gearbox is located in the engine core compartment. This location allows the nacelle diameter to be smaller for lower nacelle drag. The basic engine design will accommodate an alternate accessory location on the fan case if that arrangement is ultimately preferred by some users.

The engine nacelle is a symmetrical, long-duct, mixed-flow design that makes extensive use of lightweight composites to reduce cost and weight. Sound suppression is integrated into the inner walls of the inlet, fan frame, fan duct, core cowl, and nozzle. The thrust reverser is a directed-cascade type with no links crossing through the fan duct. When deployed, cooling air slots are opened to allow cool ambient air to enter the region aft of the blocker doors to prevent the composite material from overheating due to hot recirculating core exhaust gas. No thrust reverser is used for the core stream since the core thrust is effectively spoiled by the overexpansion of the mixer exhaust into the fan nozzle when the fan air is blocked off.

Mounting provisions permit the point mount loads to be transferred into the engine in a smooth, attenuated manner. Thrust side and vertical loads are transferred into the forward engine frame; roll side and vertical loads are taken out by the aft mount attached to the LP turbine frame.

## 1.1 PROPULSION SYSTEM DESIGN

### 1.1.1 System Integration

#### Technical Progress

Flight Loads, which are used to calculate deflections and subsequently determine buildup clearances, were reconsidered. Recent production engine flight load requirements and some Boeing 747 flight data differ from E<sup>3</sup> design loads. They indicate "g" loads are more severe and gyro loads are less severe. The judgment as to whether these loads are appropriate for E<sup>3</sup> has not been made.

Preliminary work on an FPS update has started. The update will be coordinated with WBS 1.6, Benefit/Cost analysis.

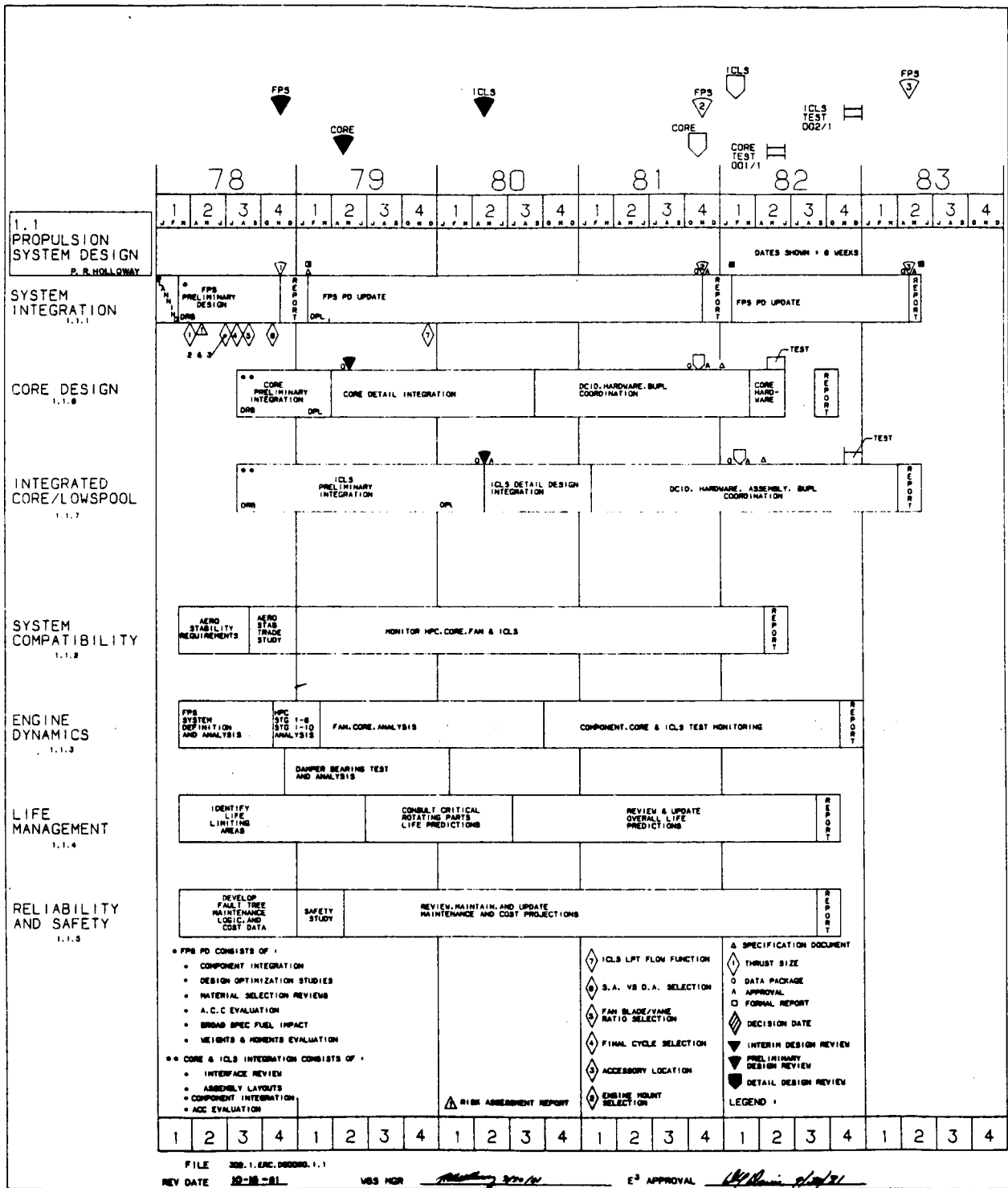
The FPS Materials drawing is shown in Figure 1.1-2.

The FPS Cooling Air and Secondary Flow drawing was updated and issued. The updated drawing is shown in Figure 1.1-3.

#### Start Analysis

Component test results and a subsequent analysis of engine starting have resulted in a greatly improved start projection.

Previously, the need for substantial bleed from Stage 7 in the compressor had been projected for starting. This resulted in overtemperaturing the outer portion of the turbine when burning only the pilot dome of the double-annular combustor. If both pilot and main domes of the combustor were lit for starting to flatten the temperature profile, the emissions characteristics of the main dome had to be sacrificed to achieve light-off.



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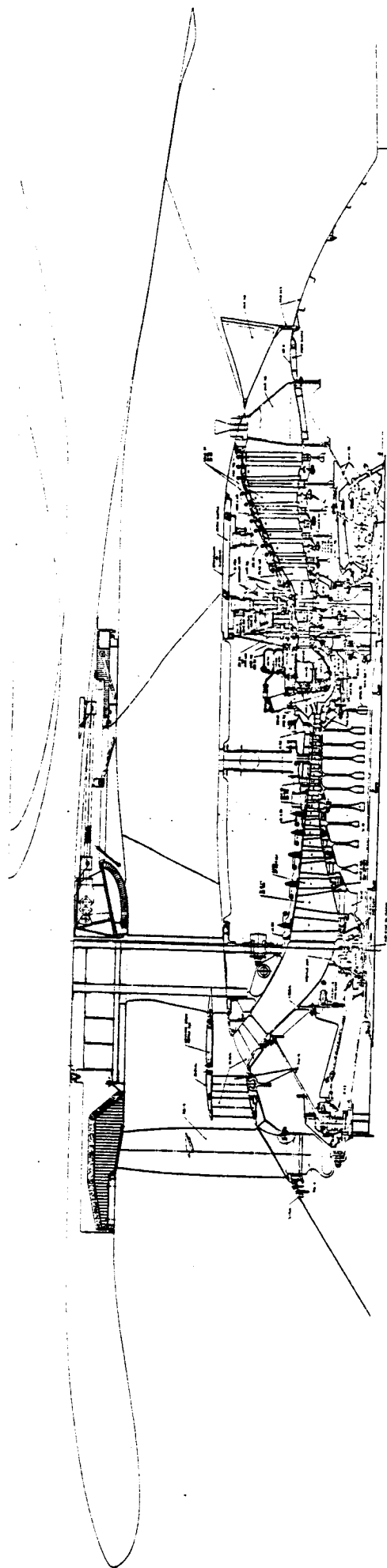


Figure 1.1-2. FPS Material Identification.

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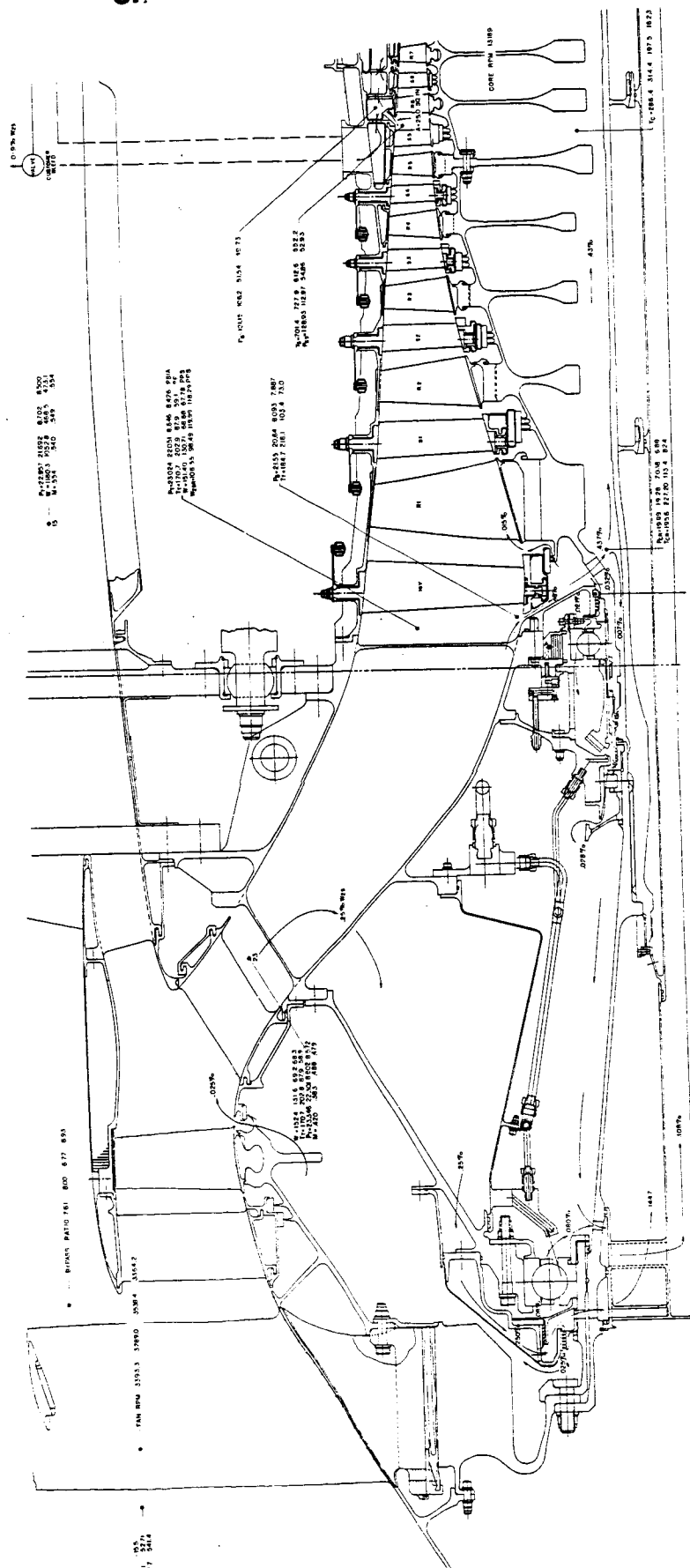
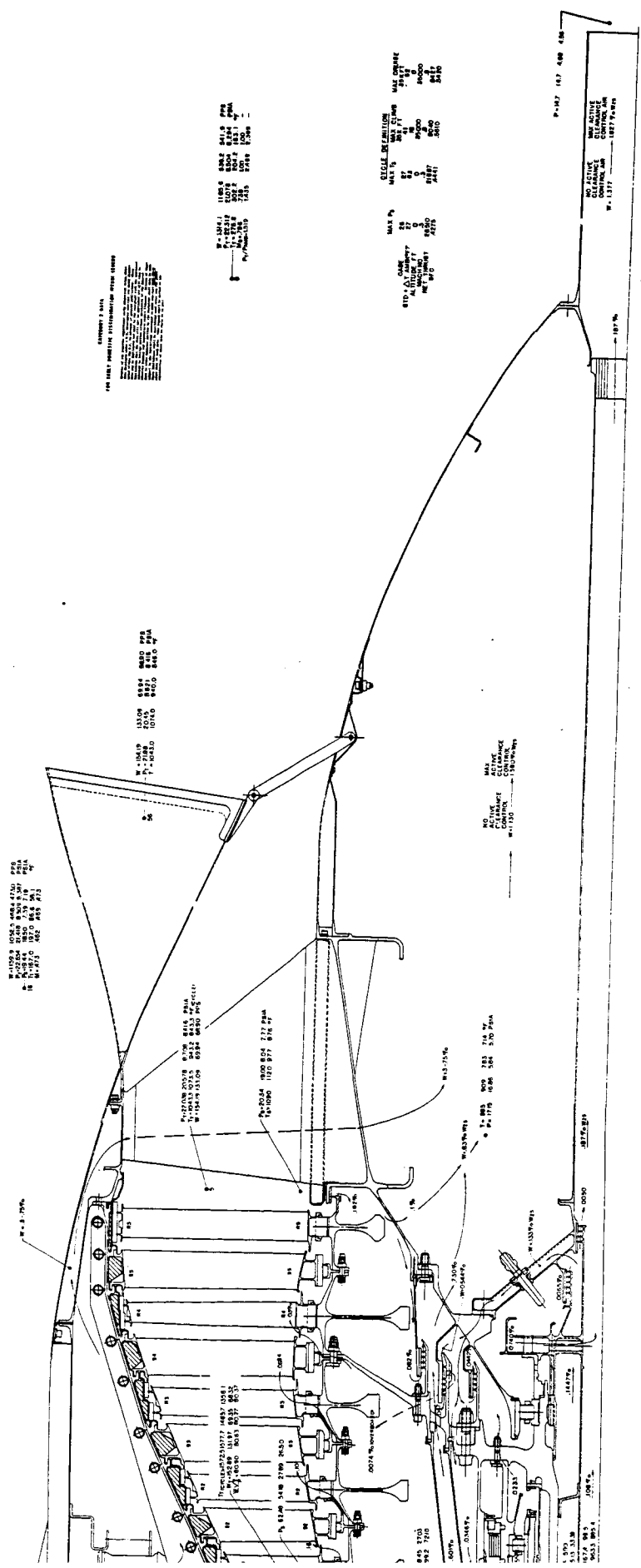
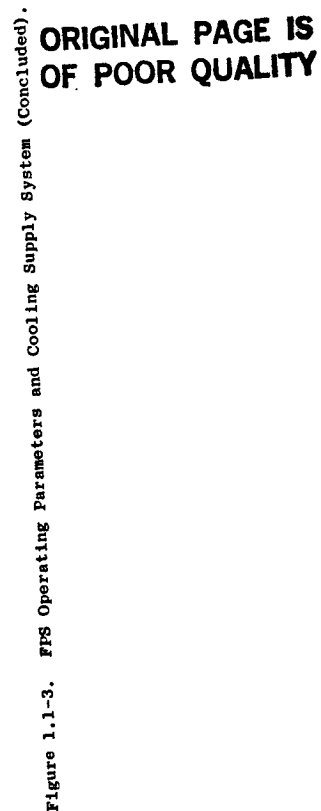


Figure 1.1-3. FPS Operating Parameters and Cooling Supply System.



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ure 1.1-3. FPS Operating Parameters and Cooling Supply System (Concluded).



**Figure 1.1-3. FPS Operating Parameters and Cooling Supply System (Concluded).**

In subsequent compressor tests, however, projected start region stall margin was achieved without bleed, and efficiency exceeded projections by 2 to 10 points, depending on the amount of stall margin selected. The high pressure turbine rig exceeded projected efficiency by 2 to 5 points in the start region.

Engine starting was reanalyzed using the rig test results. This showed starts could be satisfactorily achieved using little or no Stage 7 bleed and burning the pilot dome only.

Combustor testing was then directed at developing the combustor to operate as originally intended - using the pilot dome for starting and idle and both domes for higher power. The FPS, core, and ICLS engines will operate in this mode.

FPS weight and cost could be improved if the hardware for substantial start bleed could be eliminated. Tests showed that 5th stage bleed improved start region stall margin, although not as effectively as 7th stage bleed. Possible alternate bleed provisions, if needed, might be incorporated into Stage 5 customer bleed piping, Stage 5 cooling air supply piping, or Stage 7 cooling air piping. These options will be considered in an FPS update.

#### Work Planned

Conduct a general FPS update.

#### 1.1.2 System Compatibility

##### Technical Progress

Test plans were prepared and coordinated with aero engineering for the fan component distortion testing.

Core stability assessments were prepared for the core DDR. No stability problems are projected for the core engine.

### Work Planned

Monitor fan component distortion test and analyze the data for determining fan distortion sensitivity and transfer functions.

Monitor the 1-10 stage compressor rig test and analyze the data for determining stability characteristics of the compressor.

#### 1.1.3 Engine Dynamics

##### Technical Progress

##### Full-Scale, 10-Stage Compressor Rig

The full-scale, 10-stage compressor test program was completed without encountering any system vibration problems. Throughout the testing, the frequency response characteristics agreed with analysis predictions up to and including the maximum speed of 11,600 rpm.

The compressor vehicle employed a soft mount suspension system that provided for rotor vibration isolation. Squeeze film dampers located at the No. 1 and No. 2 bearings were utilized to dissipate the vibration energy associated with the rigid body modes. The system was designed to operate supercritical to the rigid body modes, and the soft mounts allowed the rotor to run in a dynamically stiff configuration, i.e., rotor bending did not occur over the operating speed range. The combined effect of the soft suspension system and the dampers resulted in a rotor that had a very low sensitivity to unbalance, as intended. Figure 1.1-4 illustrates the frequency response characteristics for the soft side of the No. 1 bearing support and compares the component mode analytical solution with the synchronous response during a representative test run.

A steady-state squeeze-film damper performance investigation was conducted with the vehicle operating at the critical speed. The synchronous response at the soft side of the No. 1 bearing support increased by 43% as the damper oil supply was shut off. The test results verified the effectiveness of the soft supported rotor and squeeze-film damper system to reduce unbalance sensitivity.

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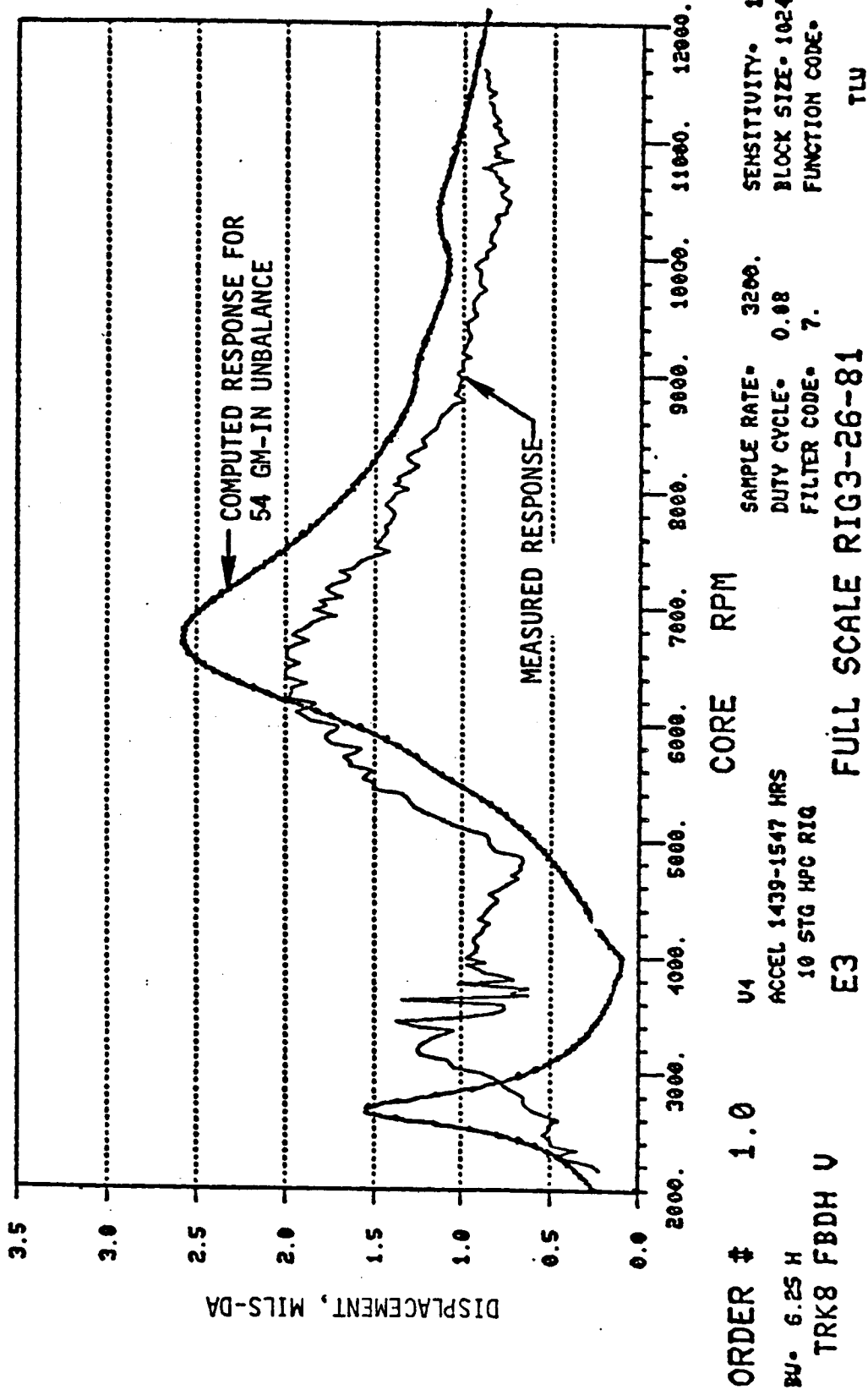


Figure 1.1-4. E<sup>3</sup> 10-Stage Compressor Rig Synchronous Response on the Forward Bearing Damper Housing, Comparison of Analysis and Test Results.

No synchronous vibration problems were encountered during the extended stall, which occurred during the final test run. The rotor remained stable and posttest FFT analysis indicated that the peak synchronous response was 1.6 mils-da at 6200 rpm at the soft side of the No. 1 bearing support.

The damped soft-mounted concept has also been designed into the core, the ICLS, and the FPS. The low vibration response of the 1-10 stage compressor vehicle served to further demonstrate the validity of this design approach.

#### Full-Scale Fan Rig

Synchronous vibration limits were established for the full-scale fan test. Accelerometers at both bearing sumps, the fan frame, forward fan case, and the island will be monitored to assure safe operation of the vehicle. Response levels are expected to be low and no vibration problems are anticipated for the test.

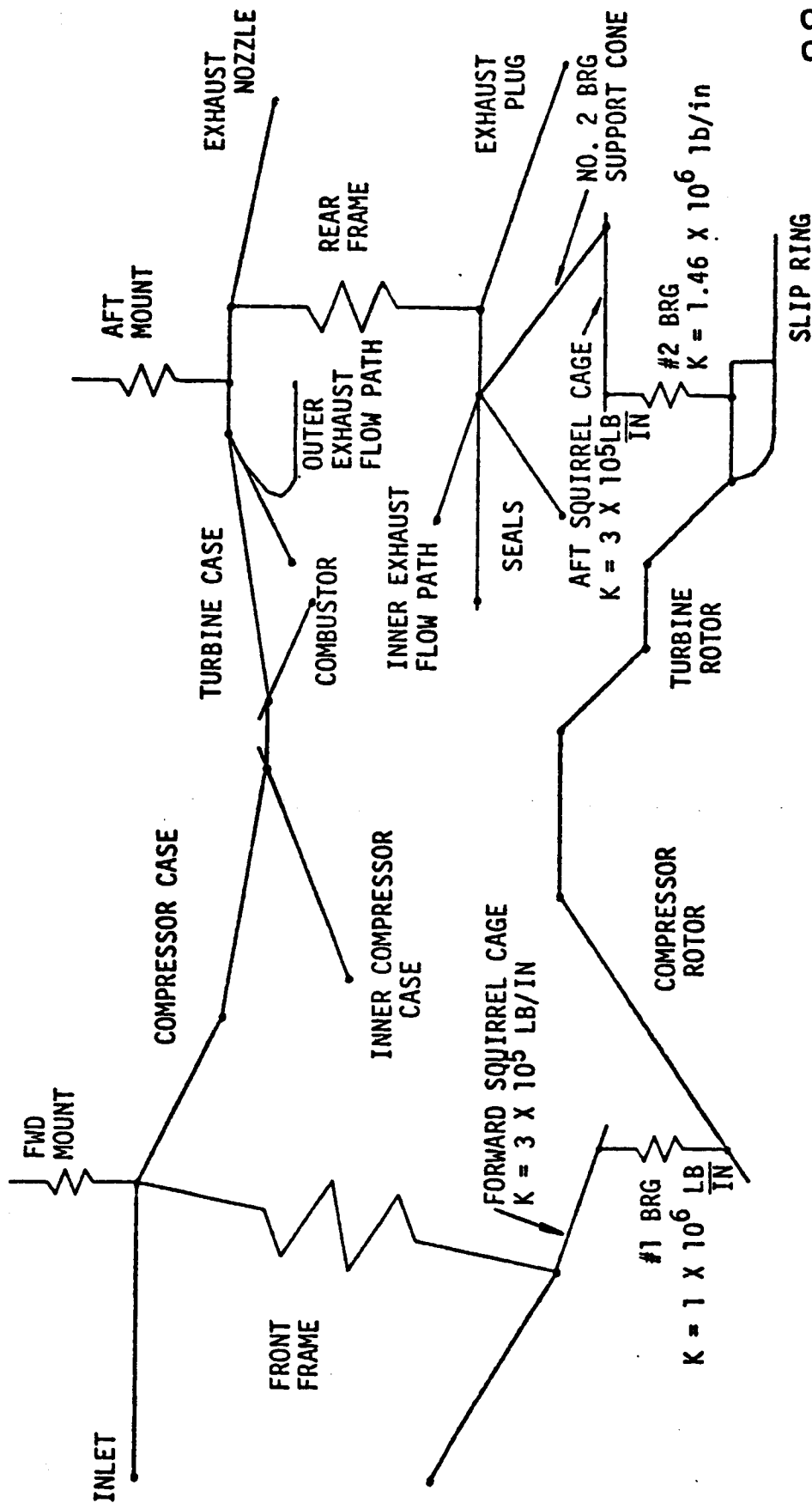
#### Core Test Vehicle

The core demonstrator vibration characteristics were summarized for the DDR. Figure 1.1-5 describes the engine system planar finite-element model used for the dynamic analysis. Figures 1.1-6 and 1.1-7 illustrate the modal deflection characteristics and provided an energy summary for the rotor rigid body modes which couple the rotor mass with the suspension system. Figures 1.1-8 through 1.1-11 illustrates the frequency response characteristics for normal and high unbalance.

Clearance requirements were defined for the test program based on both synchronous vibration response to rotor unbalance and clearance change in the vertical plane due to 1 "g" down gravity load.

#### ICLS

Clearance requirements were defined for the ICLS test program based on both synchronous vibration response to rotor unbalance and clearance change

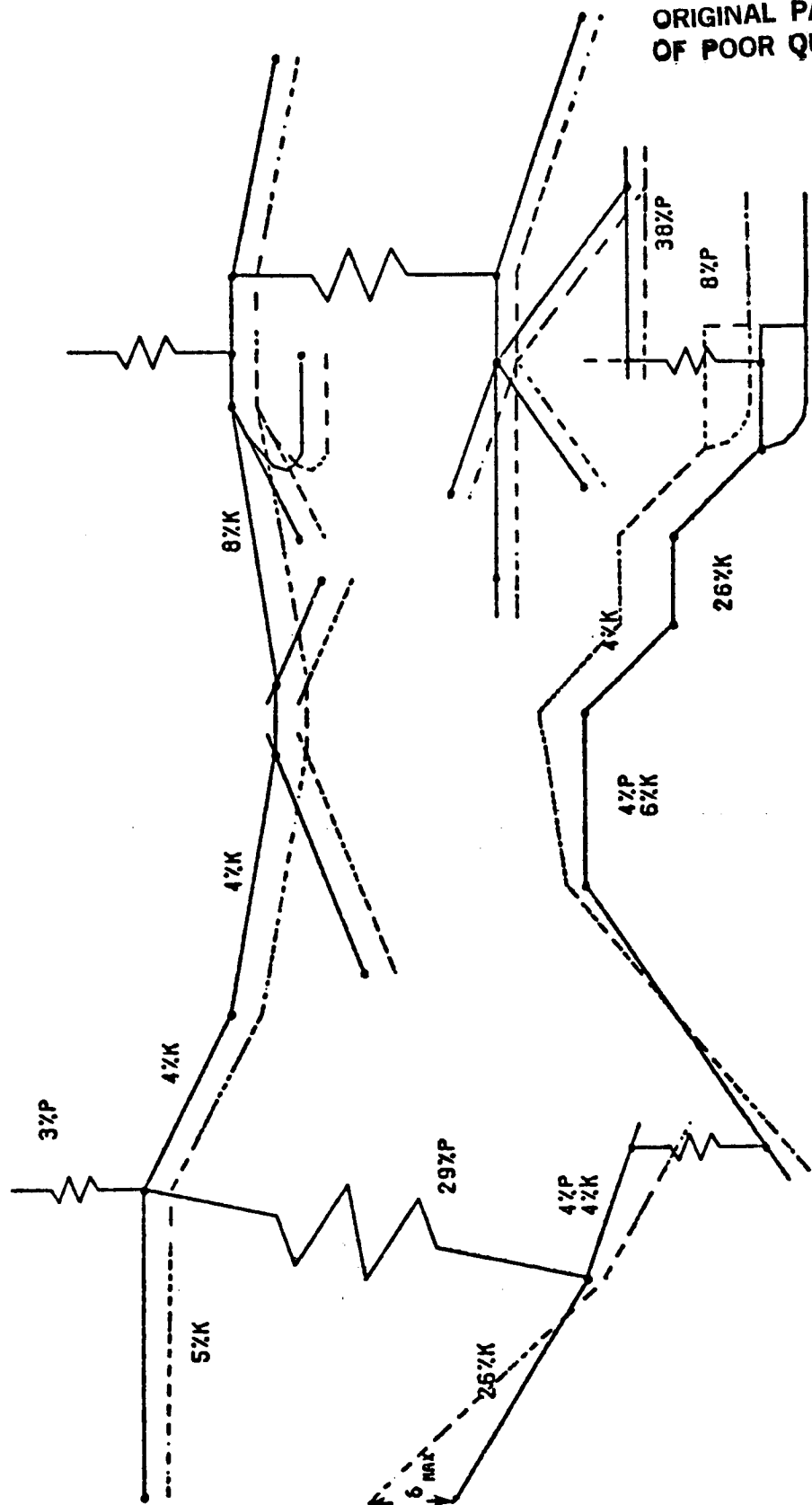


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Figure 1.1-5. E<sup>3</sup> Core Engine Vast Model Schematic.

1% PE - #1 Brg.      10% PE in rotor      8% PE - #2 Brg.  
 4% PE - Fwd squirrel cage      38% PE - Aft squirrel cage

ROTOR RIGID BODY MODE INVOLVING MASS COUPLING OF  
 ROTOR WITH SUSPENSION SYSTEM      40% KE in rotor



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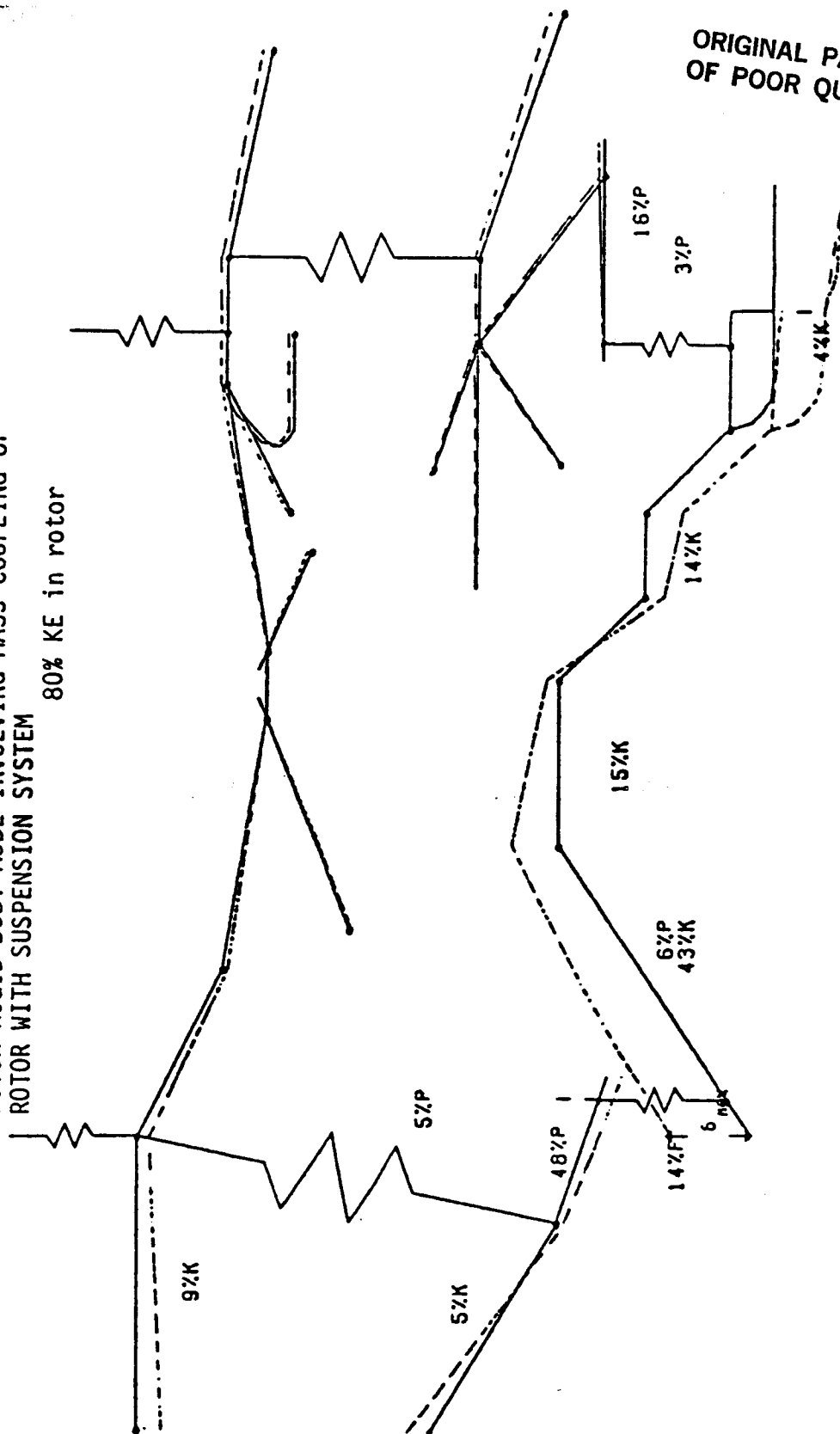
Figure 1.1-6. E<sup>3</sup> Core Engine Soft Mounted Rotor Modal Deflection for Critical Speed at 4096 RPM.

14% PE - #1 Brg.  
48% - Fwd. squirrel cage

10% PE in rotor  
3% PE - #2 Brg.  
16% PE - Aft squirrel cage

ROTOR RIGID BODY MODE INVOLVING MASS COUPLING OF  
ROTOR WITH SUSPENSION SYSTEM

80% KE in rotor



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Figure 1.1-7. E<sup>3</sup> Core Engine Soft Mounted Rotor Modal Deflection for  
Critical Speed 7180 RPM.

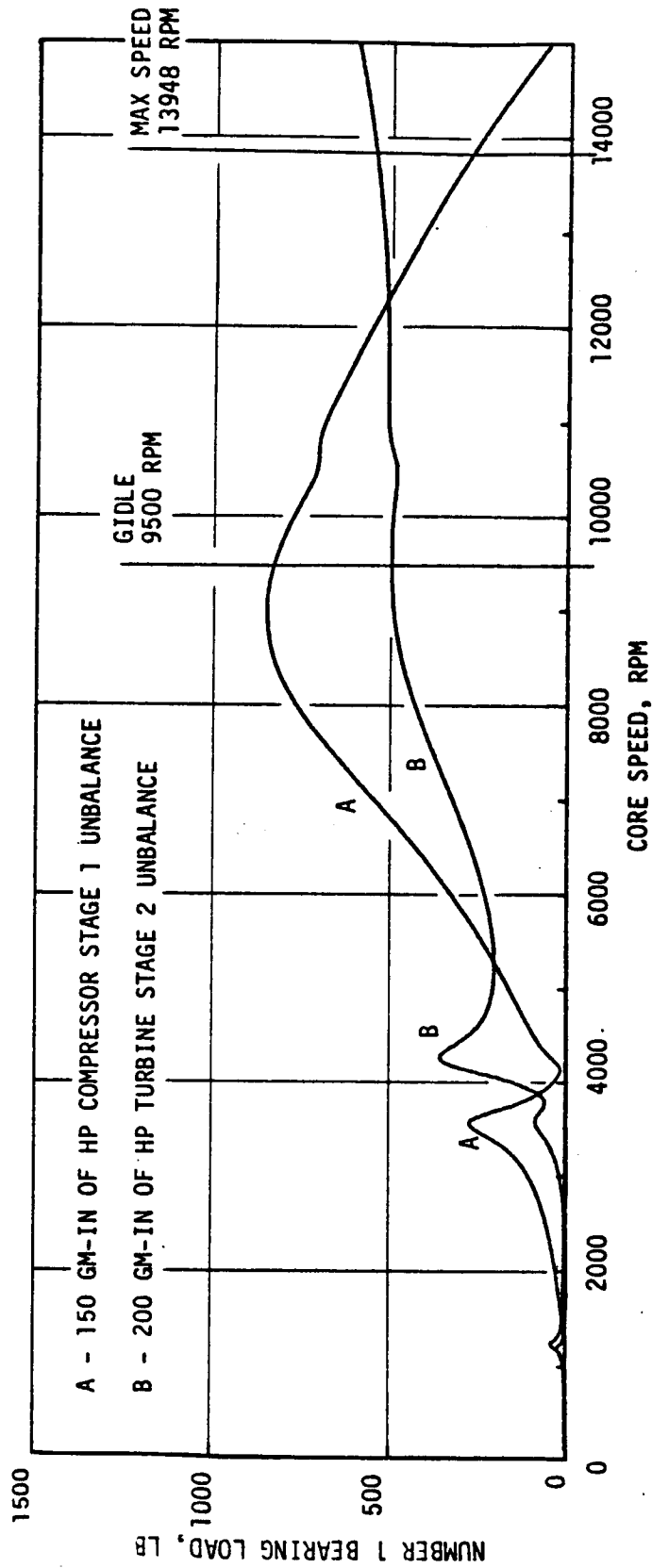
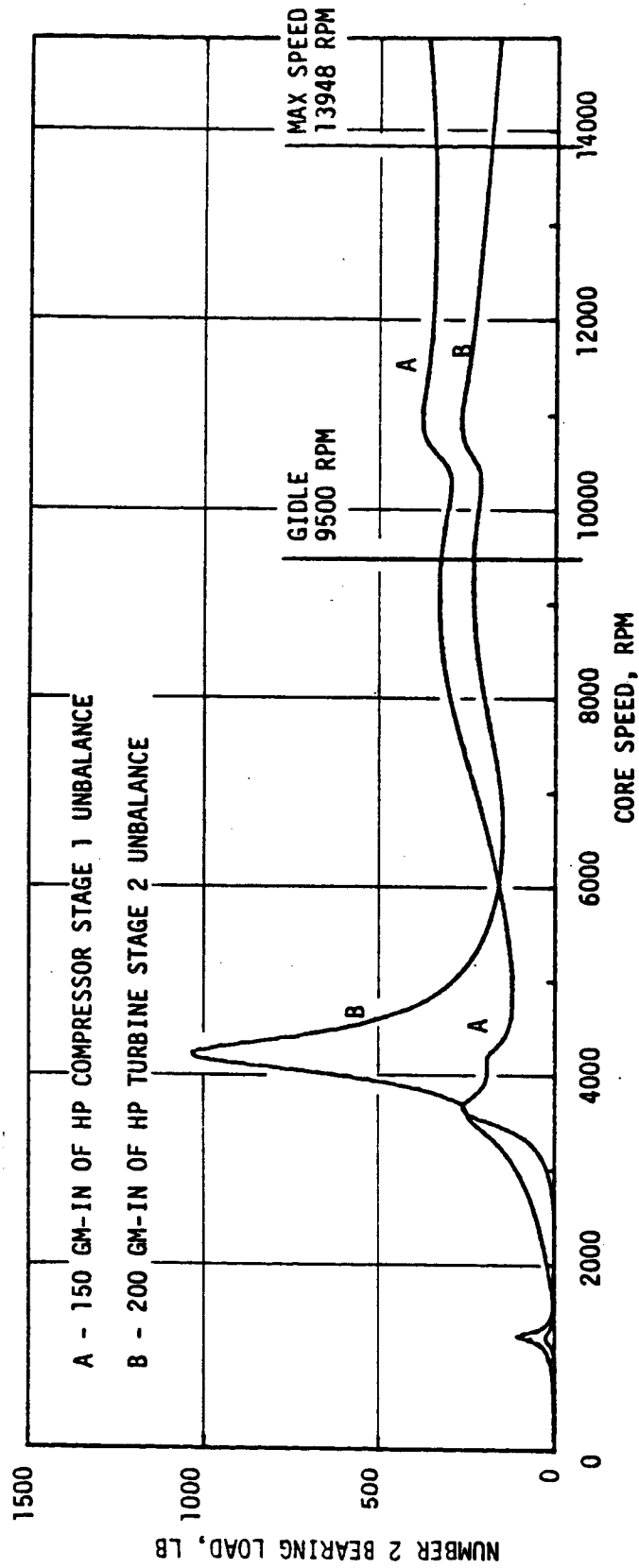


Figure 1.1-8. E3 Core Engine Synchronous Frequency Response, Number 1 Bearing Load for Normal Unbalance.

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Figure 1.1-9. E3 Core Engine Synchronous Frequency Response, Number 2 Bearing Load for Normal Unbalance.

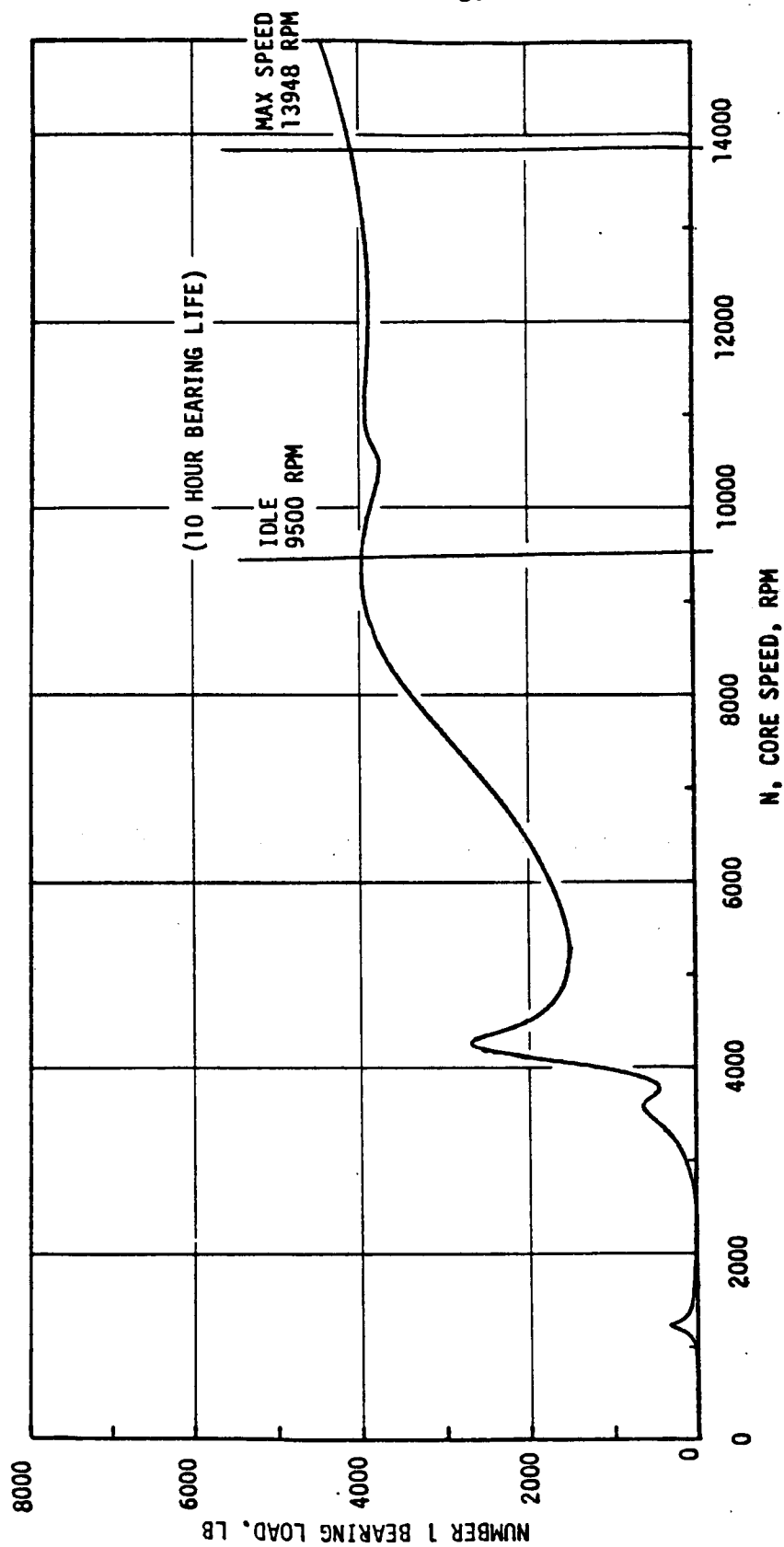


Figure 1.1-10. E<sup>3</sup> Core Demonstrator Synchronous Frequency Response, 1500 gm-in. of HP Turbine Stage 2 Unbalance No. 1 Bearing Load.

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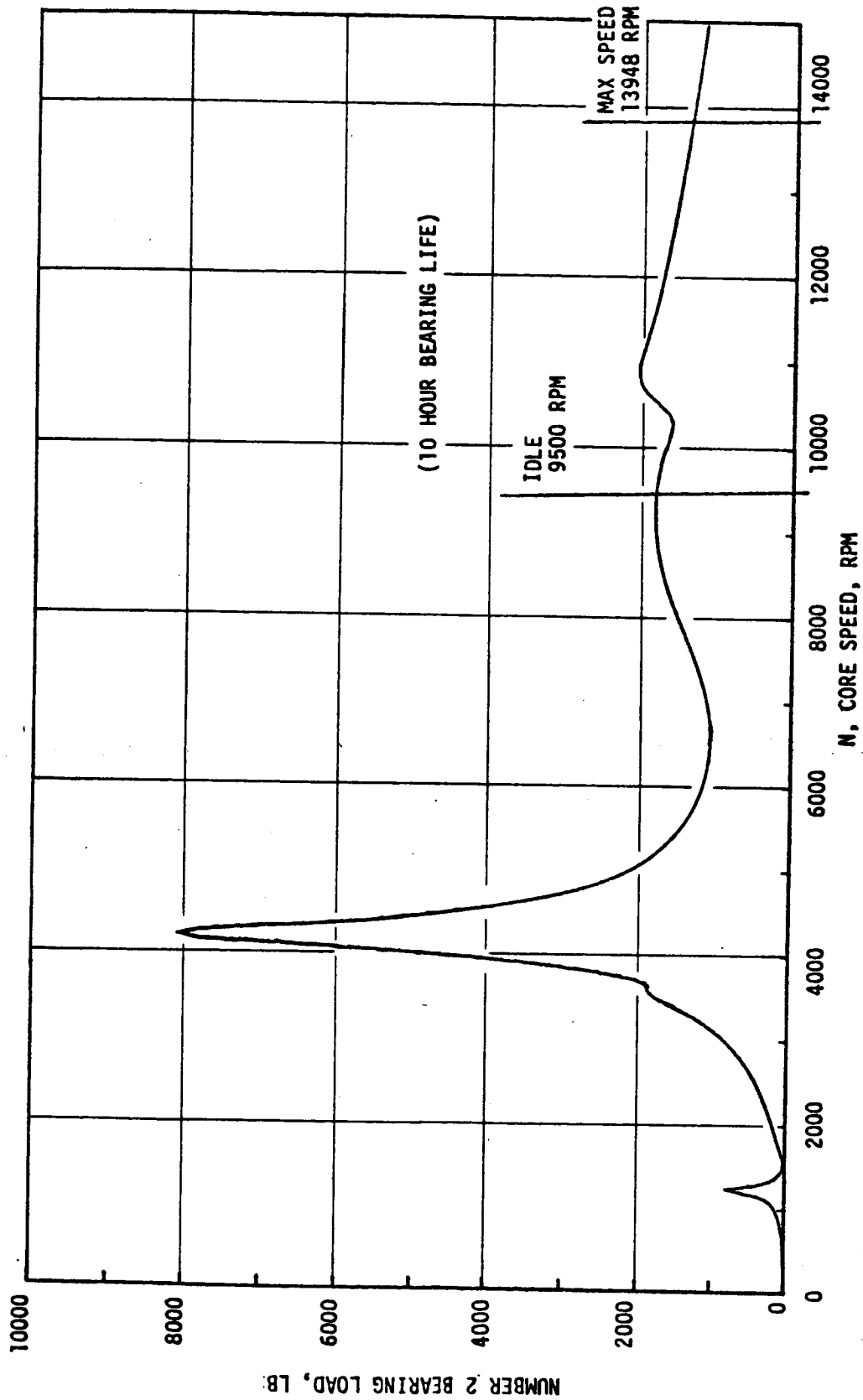


Figure 1.1-11. E<sup>3</sup> Core Demonstrator Synchronous Frequency Response, 1500 gm-in. of HP Turbine Stage 2 Unbalance No. 2 Bearing Load.

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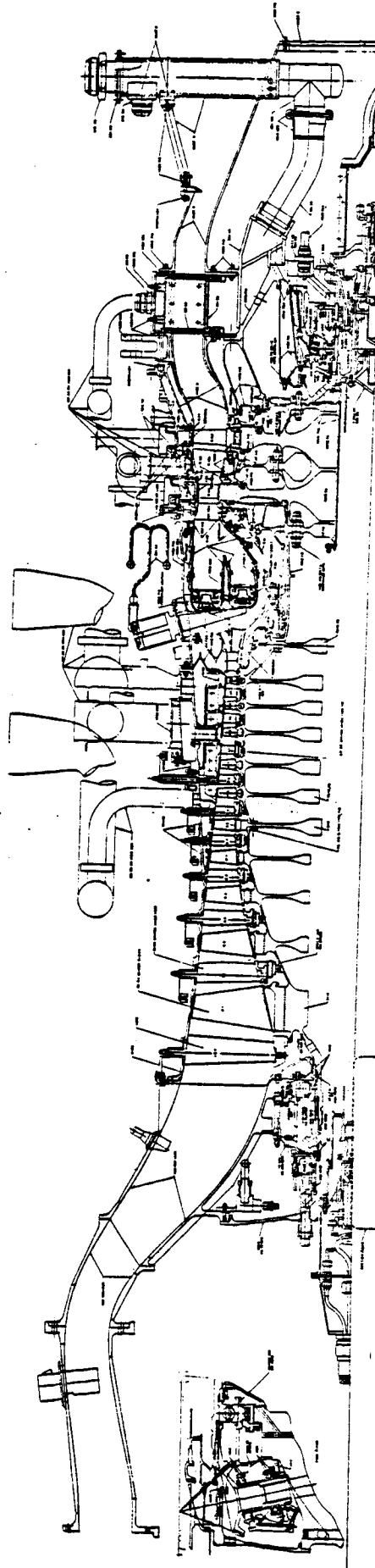


Figure 1.1-13. Core Engine Materials Identification.

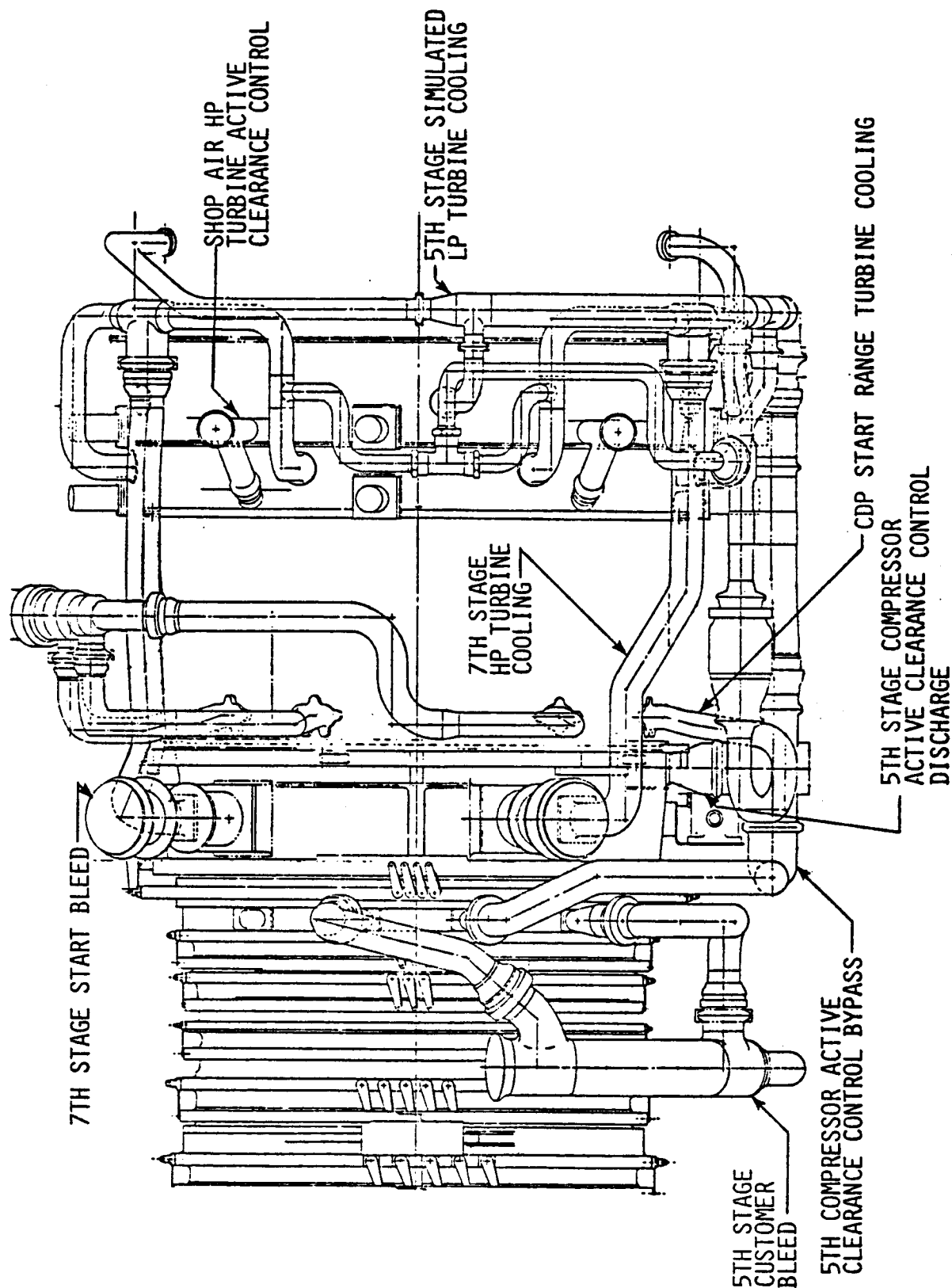


Figure 1.1-14. Core Engine Piping.

limit on clearances is an acceleration "pinch point" so this, calculated for the ICLS engine, will be the basis for setting clearances. The same hardware, and therefore the same clearances, are used in the core.

An engine assembly and machining sequence has been established to ensure that casings and bearing bores are on a common centerline. Starting with the front frame, the outer shell structure will be assembled on a VTL. As each major shell is added to the stack, flanges, rabbets, and bearing bores will be machined to the stack centerline. Reference diameters and surfaces will also be machined so that they can be used to set up subsequent subassembly level machining of items such as seals which are not accessible in the full stack. Drawings and plans to execute this have been established.

Because of excessive cost, customer bleed piping for compressor discharge pressure air has been eliminated from the core. Slave piping will be retained for 5th stage customer bleed, primarily for exploring the effects of bleed on aero-mechanical stability.

Because of excessive cost, piping for the HP turbine active clearance control air will be provided by facilities engineering. This piping provides shop air, simulating fan air, to the impingement manifold. It previously had been flight-type constructional though not an actual flight design.

The FPS engine uses a heating circuit for the high pressure turbine active clearance control system. This circuit pipes CDP air into the ACC manifold during early warm up to avoid a rub if high power should be set before the engine is fully warmed up. Adding this circuit to the core was considered. The decision was made not to add it to the core because this type of transient is not planned for the core and therefore, the extra costs could be avoided.

Exhaust nozzle effective area will not be varied by injecting air or steam as had been considered. Instead, the physical area of the nozzle will be varied. Two nozzles of different areas are being procured and a larger area can be set by deleting the nozzle piece completely. These nozzles are expected to be trimmed to set operating lines.

All core assembly drawings have been issued except the clearance drawing.

Preparations for the core DDR are largely complete. It will be presented in late October or early November 1981.

#### Work Planned

Continue coordination. Conduct the Core DDR.

#### 1.1.7 ICLS Analysis and Design

##### Technical Progress

The ICLS cross section is shown in Figure 1.1-15. The ICLS operating parameters and cooling air drawing and the materials drawing were updated. They are shown in Figures 1.1-16 and 1.1-17, respectively. Because of excessive cost, customer bleed piping for both 5th stage air and CDP air have been eliminated from ICLS. Customer bleed is explored in compressor rig testing, and to a lesser extent in the core, and is not necessary in the ICLS engine.

The ICLS multiple engine buildup lists (MEBUL) has been made operative. The engine parts lists are now under DCID control.

Some bearing cavity seals had less pressure difference across them at idle than is standard GE design practice. To provide safe margin in the first engine to test, the capability to pressurize the sump flow circuit with shop air during idle is being provided.

Nozzle tests showed that static pressure at the exhaust stinger was higher than expected. The stinger is, therefore, being extended aft. Also, the stinger diameter is being increased, primarily to accommodate cooling air from the aft slipring.

The master stack nomenclature/reference drawing series (completed for the core engine) is being expanded to cover the LP system in ICLS. These will provide explicit definition of all axial drops, surfaces, diameters, and radii involved in key interfaces, clearances, and axis alignments. The initial application will be to establish and review specific options for ICLS centerlining operations.

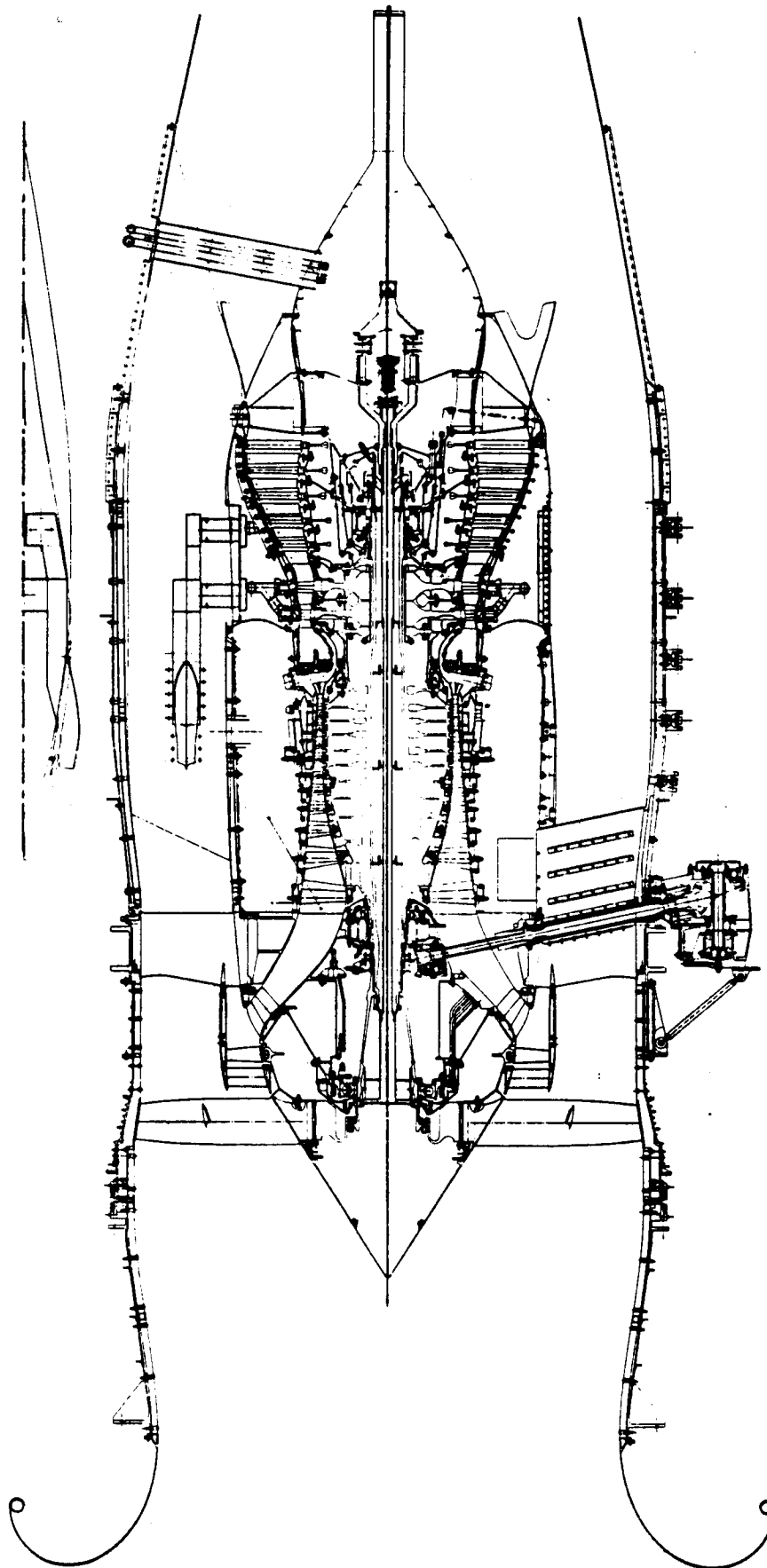
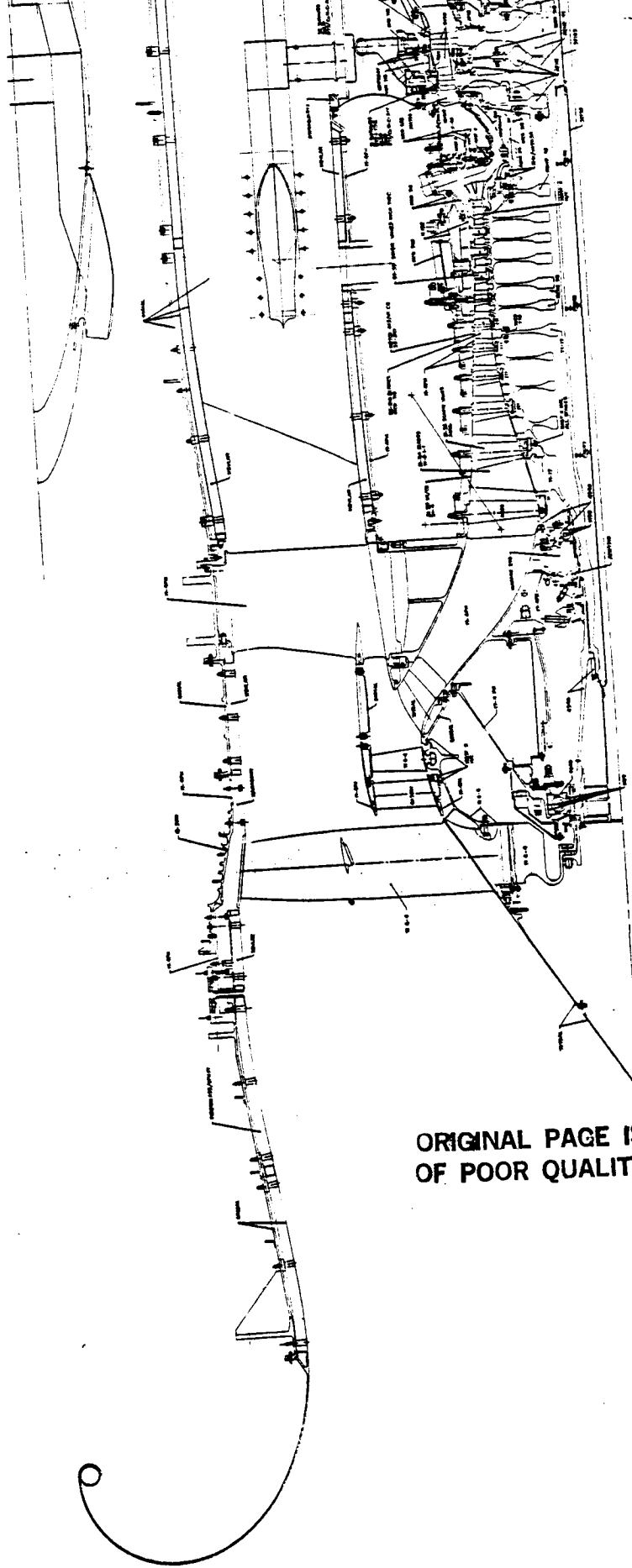


Figure 1.1-15. ICLS Cross Section.



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Figure 1.1-17. ICS Material Identification.

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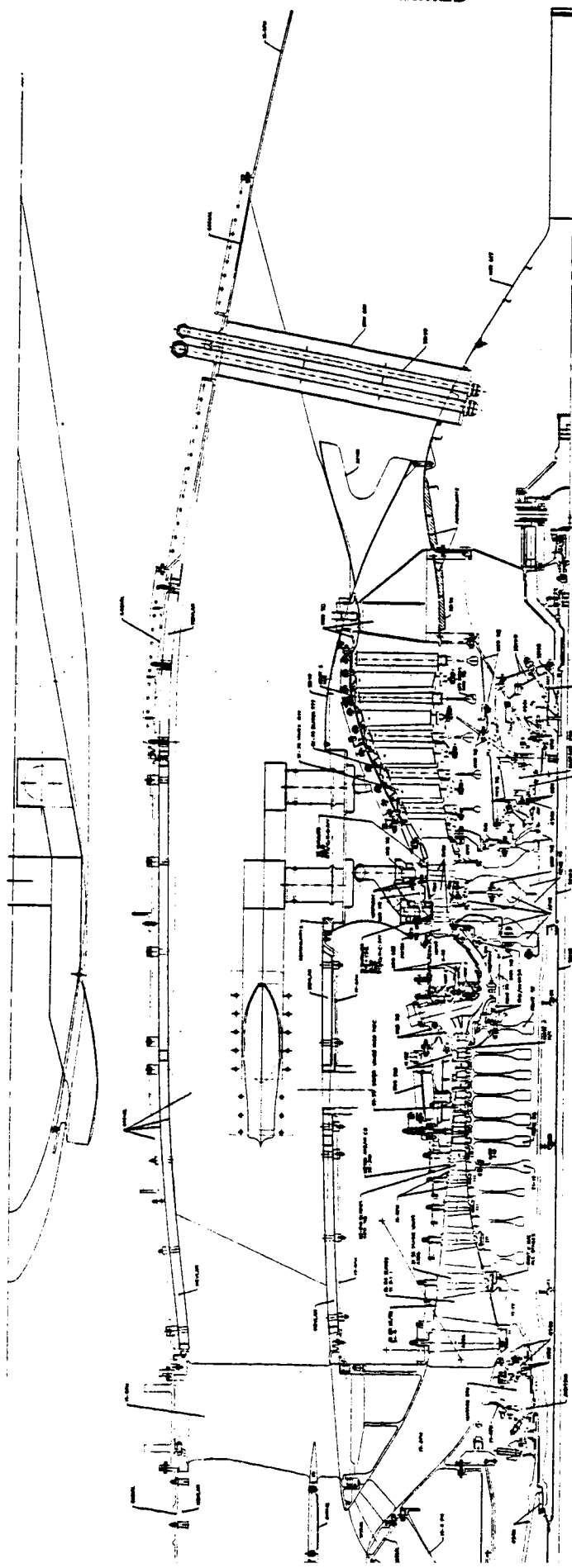


Figure 1.1-17. ICLB Material Identification.

Design of the ICLS engine mount lugs and facility mount links was completed. One interference between the mount structure and engine was discovered and corrected.

An interference between low pressure turbine cooling air piping and the LPT active clearance control manifold, which is integral with the core cowl, was discovered. This is being resolved by changing the pipe design in the upper half of the engine and changing the manifold design in the lower half.

For fire safety considerations, ways to drain fluids which could accumulate in the core cowl are being investigated.

The criteria for buildup clearances has changed. See Section 1.1.6 for discussion.

#### Work Planned

Continue integration and coordination.

### 1.2 CYCLE AND PERFORMANCE

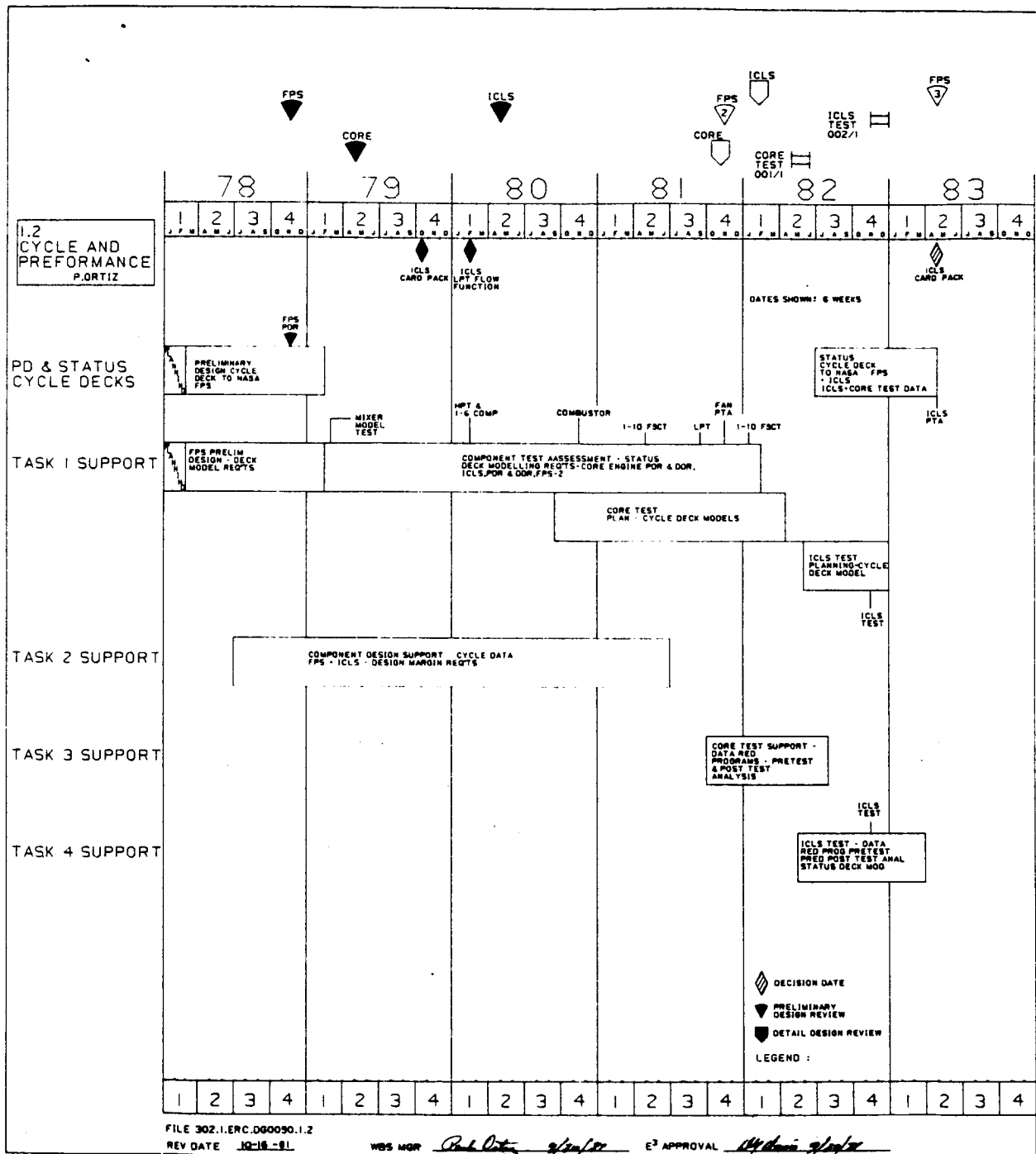
#### Technical Progress

The effort during this reporting period has been concerned with three primary tasks: updating the engine status cycle deck, supporting the core engine test planning activities, and preparing the core engine DDR material. In addition to these tasks, a preliminary investigation was made into windmilling estimates of the E<sup>3</sup> FPS to define altitude relight conditions for the combustor test program.

#### Status Cycle Deck

The status cycle deck logic modifications were defined in Semiannual Report No. 6 and were shown as completed except for the active clearance control (ACC) model. This ACC model has been completed and is currently in checkout.

The ACC system modeled consists of a number of subroutines that calculate rotor and shroud growth for the HPC, HPT, and LPT as a function of the



driving variables in the engine. In each component, a key stage is used to calculate the expected clearance for that stage. The remaining stage clearances are then calculated as a function of the key stage. The component efficiency from the baseline performance map is then modified as a function of clearance change from the nominal value used for the performance map.

The model was developed from the detailed dynamic modeling of the engine and showed an excellent correlation over a wide range of flight conditions.

A number of modifications have been made to the status cycle deck model to update the ICLS performance. The HPT map defined from the rig test has been modeled and incorporated into the cycle deck. The compressor map characteristics have been modified for the core engine HPC performance projection. The fan map has been modified in the low power region based on updated data from other engine tests. New nozzle coefficients based on the Fluidyne tests have been incorporated for the ICLS performance update.

An updated ICLS-5A forecast cycle has been defined using the component status performance levels. This represents a properly matched flight engine using ICLS status performance levels. Table 1.2-I shows a comparison of the ICLS-5A cycle with the FPS-4 cycle. The FPS-4 cycle has not been updated and remains as shown in Tables 1.2-I and 1.2-II.

#### Core Test Planning

Support is continuing for the core test planning activities. Instrumentation design is being reviewed along with facility support services which will be used in conjunction with the test and which have an impact on the performance analysis. Facility air will be used to cool touch probes in the compressor casing and may inject some small amount of inflow into the compressor. In addition, some compressor discharge air will be used to cool the HPT clearance measurements probes and will enter the HPT flow stream.

Work will continue on assessing performance losses for instrumentation. The HPT discharge radial probes pressure losses were assessed in the LPT rig tests and will be used in sizing the core engine nozzle area.

Table 1.2-I. FPS and ICLS Maximum Cruise Cycle Comparison.

35,000 Feet/0.8 Mach/Standard Day + 18° F.

Parameter	FPS-4	ICLS-5A* Forecast
Uninstalled Performance		
Net Thrust, lb	8425	8425
SFC (Standard Day)	0.542	0.554
Bypass Ratio	6.95	6.94
Fan		
Corrected Flow, lb/sec	1396	1396
Bypass Pressure Ratio	1.61	1.61
Hub Pressure Ratio	1.63	1.64
Compressor		
Corrected Flow, lb/sec	118.0	117.3
Pressure Ratio	22.4	22.3
HP Turbine		
Flow Function, $W\sqrt{T/P}$	17.6	17.6
Rotor Inlet Temperature, ° F	2277	2319
LP Turbine		
Flow Function, $W\sqrt{T/P}$	80.3 (Base)	80.8 (+0.6%)
Nozzle Inlet Temperature, ° F	1438	1464
*ICLS-5A is a flight engine properly matched for the component performance levels defined.		

Table 1.2-II. FPS-4 Performance Parameters.

Parameter	Maximum Climb 35,000 feet/ 0.8 M/+18° F	Maximum Cruise 35,000 feet/ 0.8 M/+18° F	Takeoff SLS/+27° F
Net Thrust, lb	9040	8425	36500
SFC (Standard Day)	0.546	0.542	0.294
Bypass Ratio	6.77	6.95	7.34
Overall Pressure Ratio	37.7	35.8	29.7
Fan Bypass Pressure Ratio	1.65	1.61	1.50
Compressor Corrected Airflow, lb/sec	120.0	118.0	108.9
Compressor Pressure Ratio	23.0	22.4	20.0
HPT Rotor Inlet Temperature, ° F	2345	2277	2450

### Core Engine DDR

Preparation of the performance analysis section of the DDR has been completed.

### Altitude Relight

An investigation was made into the expected windmilling characteristics of the E<sup>3</sup> FPS in order to predict conditions for combustion altitude relight. The specific parameters of concern were P3 and combustion airflow as a function of flight Mach number and altitude. A number of altitude relight envelopes were reviewed for other high bypass engines, and it was found that E<sup>3</sup> would approximate the characteristics shown for the CF6-6 engine. It was recommended that this map be used with a slight reduction in the compressor flow levels shown.

### 1.3 MATERIALS AND PROCESSES

#### 1.3.1 Materials and Processes Component Support

##### Technical Progress

The metallurgical support activities for each component will be described individually. Most of the components either went to test or are in final stages of buildup for test; consequently, only limited metallurgical support was required during this reporting period for the component tests.

##### HP Compressor 1-10 Rig Test

A failure analysis investigation was conducted indicating the foreign object damage sustained during the first 1-10 rig test was caused by non-metallic "soft-body" impact. Other activities included the recambering and/or the stripping of instrumentation from the blades and vanes for the rebuild of the rig which goes to test in December.

##### Full-Scale Fan

Manufacture is complete. Most activities on this component during this reporting period were involved in the preparation of the vehicle for the September test; provided support for the "fix" on the frozen tie bolt.

##### Combustor Test Rig

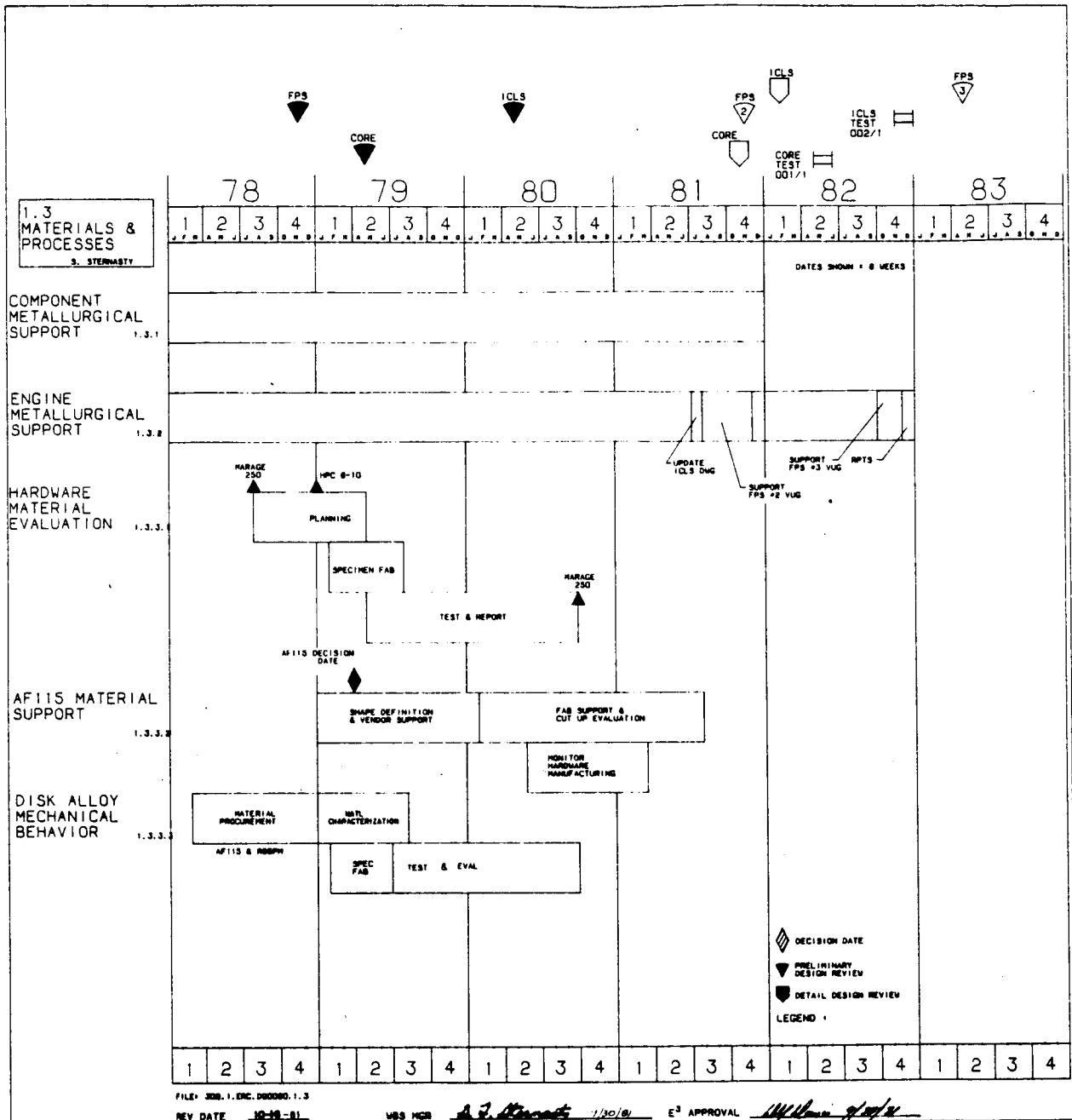
No materials support was required on the combustor test rig during this reporting period.

##### LP Air Turbine

Identified a successful epoxy adhesive repair for the brazed honeycomb; this rig is on test.

##### Work Planned

Support on component tests will continue, including the buildup of the 1-10 rig. Primarily, support during the next reporting period will involve evaluation of hardware from component tests, as required.



### 1.3.2 Materials and Processes Engine Support

This section describes the technical progress accomplished in support of the core, ICLS, and FPS engines. The major items of technical support are as follows:

#### Material Selection

There were no changes in materials for the engines during this reporting period.

#### Support Activities

Material and process drawing definitions continued to be provided for the engines. Numerous detail drawings were issued including the No. 5 bearing housing, compressor vane assemblies, VSV actuation system, configurations, Stage 2-5 compressor vanes and Stage 8-9 compressor blades.

The manufacture of hardware for the engines was closely monitored; some of the specific support activities required were:

- Identification of repair procedures for
  1. Incoloy 903A inducer seal
  2. Inconel 718 wishbone
  3. Inconel 718 LPT Stage 2 seal
  4. Compressor blade platform edges
- Participation in decision to run nonanodized aluminum hardware in ICLS which eliminates the need for post fan test teardown.
- Definition of evaluation of tip cap braze procedures on Stage 2 HPT blades.
- Evaluation of shot peen procedures on HPT disks.
- Visited vendors to review and resolve specific hardware problems as follows:
  1. Defined manufacturing process for the HPT active clearance control manifold.
  2. Evaluated first trial casting of diffuser and participated in changes resulting in success on next trial casting.

Coordination was provided between Design Engineering and the Material and Process Technology Laboratories on supporting technology programs; capsule status is as follows (details of these programs are in the appropriate WBS sections):

WBS 1.3.3.1 Hardware Material Evaluation complete. Evaluation of HPC rotor was cancelled.

WBS 1.3.3.2 AF115 Support. All testing complete; data being analyzed.

WBS 1.3.3.3 Disk Alloy Mechanical Behavior complete.

WBS 2.2.7.1 VSV Bushing. Materials selection, evaluation, and endurance testing complete except for one test.

WBS 2.4.7.1.1 Ceramic Shroud Process. Configuration, materials, and processes defined. Evaluating applicability of various NDE techniques.

WBS 2.4.7.2.1 Thermal Barrier Process. Planned engine testing of coated blades and vanes is complete. Laboratory evaluation of hardware being conducted.

WBS 2.4.7.3.1 Alloy Mechanical Behavior complete. Work on complex fatigue effects was cancelled.

#### 1.3.3.2 AF115 Support

##### Technical Progress

All the AF115 compacts have been delivered from both Crucible and Special Metals and are being machined into hardware. The LCF testing to characterize the capability of Special Metal's AF115 has been completed. The test results are tabulated in Table 1.3-I. These results are similar to those obtained from the previously tested AF115 supplied by Crucible.

##### Work Planned

Technical effort now complete.

Table 1.3-I. AF115 LCF Data (Special Metals Material).

Spec. #	Total Strain (%) $\Delta\epsilon_T$	Modulus ( $\times 10^{-6}$ ) E	$\frac{(\Delta\epsilon_T)_E}{2}$ (psi) Alt. Pseudo $\sigma$	Cycles to Failure $N_F$
1780-1	0.78	27.4	106.9	7552
1780-2	0.66	27.8	91.7	>55390*
1780-3	0.60	27.6	82.8	38073
1780-4	0.66	28.0	92.4	38614
1770-1	0.78	27.8	108.4	46264
1770-2	0.66	27.9	92.0	25564
1770-3	0.60	27.8	83.4	>122706*
1770-4	0.90	27.8	125.1	5520
1760-1	0.78	28.1	109.6	4950
1760-2	0.66	27.6	91.1	11944

1000° F, A = 1, strain control, 20 cpm

\*Specimen failed at button head, not in gage section.

#### 1.4 ACOUSTIC DEVELOPMENT

##### 1.4.1 System Acoustic Prediction

###### Technical Progress

No activity during this reporting period.

###### Worked Planned

System prediction update.

##### 1.4.3 Mixer Acoustic Testing

###### Technical Progress

Acoustic design definition for the ICLS bulk absorber treatment has been completed. The results are shown in Table 1.4-I.

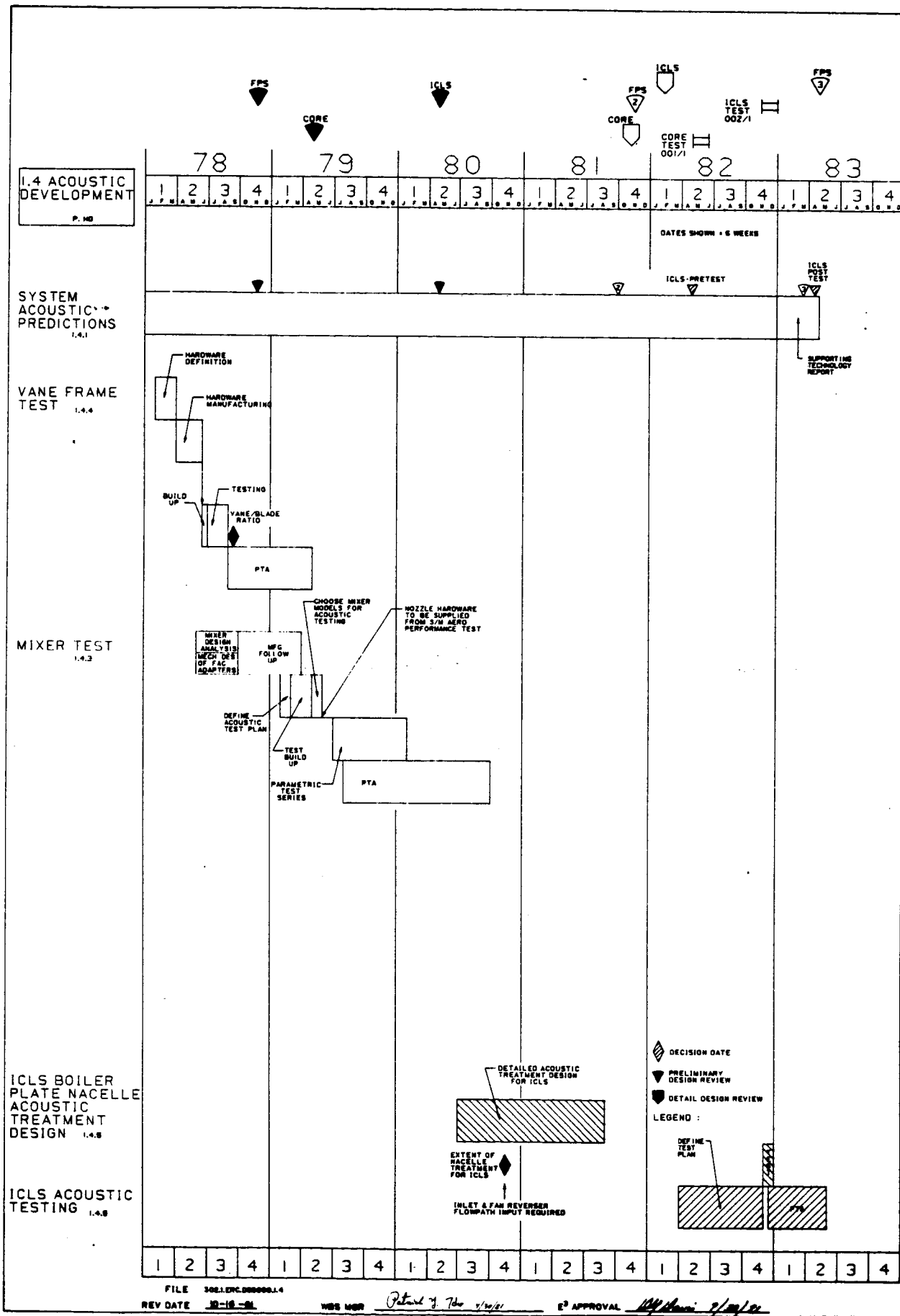
###### Work Planned

None.

Table 1.4-I. Bulk Material for ICLS.

Treatment Area	Kevlar	Astroquartz
Fan Inlet	1A & 3B	
Fan Exhaust Outer Wall	4C	
Fan Exhaust Core Cowl		1D
Core Exhaust		1E
A: 0.25-inch thick at 7 lbm/ft <sup>3</sup> B: 0.25-inch thick at 4 lbm/ft <sup>3</sup> C: 0.25-inch thick at 2 lbm/ft <sup>3</sup> D: 1.00-inch thick at 1.15 lbm/ft <sup>3</sup> E: 0.50-inch thick at 1.5 lbm/ft <sup>3</sup>		

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#### 1.5.1.1 Economics and Design

##### Technical Progress

No significant activity occurred during this reporting period. However, a general update of the FPS is being resumed and an economic update will be included.

##### Work Planned

Conduct an economic update.

#### 1.5.1.2 Installation Aero Design

##### Technical Progress

No technical activity occurred in the installation aero design during this reporting period.

##### Work Planned

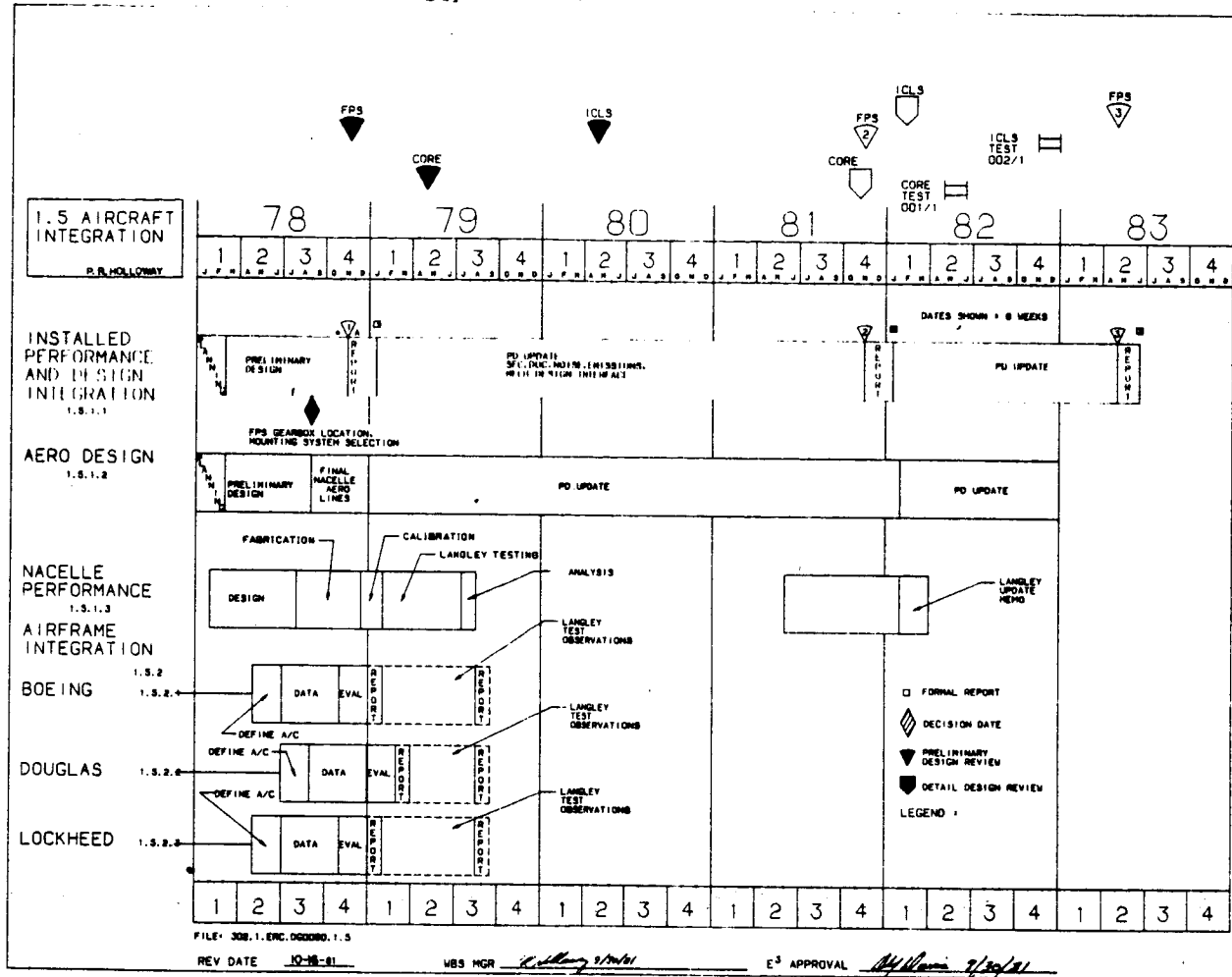
Provide installation aero design support as required.

#### 1.5.1.3 Nacelle Performance Evaluation - Langley

##### Technical Progress

Phase II test results have been received from NASA-Langley, and a contract extension was obtained to analyze calibration results and determine the cause for a shift in the  $E^3$  extended nacelle calibration coefficients. Detailed analysis of the calibration data resulted in the conclusion that the shift in the  $E^3$  extended nacelle flow and velocity coefficients from Calibration 1 to Calibration 2 was a real shift and not a measurement error. The shift apparently occurred due to a different alignment of the nozzle parts when they were reassembled on the simulator. A thorough comparison of the wind tunnel data with the calibration data provided no indication as to which calibration, if either, is valid for the wind tunnel test data reduction. It was recommended to NASA Langley that both sets of calibration data be used to

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reduce the wind tunnel test isolated nacelle data. If results from using one of the calibrations shows good correlation with the basic E<sup>3</sup> nacelle isolated data, then this might be good justification to use that calibration for the installed wind tunnel test data. If this proves unsatisfactory, then it was recommended that the E<sup>3</sup> extended nacelle be dropped from the final results of this program. A memo summarizing the study was prepared and sent to NASA-Langley.

#### Work Planned

Analyze the Phase II wind tunnel test results and prepare a data memo.

## 2.0 TASK 2 - COMPONENT ANALYSIS DESIGN AND DEVELOPMENT

### 2.1 FAN

#### Overall Objectives

The primary objective of the fan development effort is to evolve a high technology design able to meet or exceed all commercial certification requirements for noise, performance, life, and bird or ice ingestion. The general configuration of the fan (Figure 2.1-1) will incorporate a high-bypass fan stage with a part-span shroud followed by a quarter stage to provide additional supercharging to the core compressor. The design of the quarter stage, and passages aft of it, will minimize foreign object ingestion into the high-pressure compressor. The quarter stage will also provide good distortion attenuation and tolerance to bypass variation without variable geometry.

Blades will be solid titanium construction to provide the lightest weight fan capable of meeting the operational environment imposed by bird ingestion requirements. The fan will have no life-limiting conditions for the expected operation in commercial service including crosswinds, thrust reversals, and tip rubs. The FPS fan efficiency goals are 0.882 bypass and 0.892 hub at Mach 0.8, 35,000-foot altitude, standard day, maximum power setting.

The fully instrumented, full-scale test to verify the fan design began in late September 1981. Test duration is expected to be 5 to 6 weeks.

Preliminary mechanical design studies were conducted to establish the general fan configuration with the best potential for meeting the overall program objectives. In June 1979, the fan-blade parameters related to bird-ingestion tolerance were evaluated based on commercial service experience with improved blade designs now in production. The objective of this selection was to ensure that the E<sup>3</sup> fan blading design was compatible with commercial engine certification requirements.

The final aerodynamic design of the fan rotor was completed during the third quarter of 1979. The final mechanical design was completed in the fourth quarter of 1979 with an Interim Design Review (IDR) in 1979 leading

2.1  
FAN

R. BUCY

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POR  
FRAME & ROTOR  
AERO  
DESIGN

IDR

DDR

DATES SHOWN = 6 WEEKS

PRELIMINARY  
MECH DESIGN

ROTOR  
MECHANICAL  
DESIGN

ROTOR  
FAB

FAN FRAME FABRICATION  
(ICLS HARDWARE)

FAN BLADE/VANE RATIO  
DEC PT

FAN BLADE BIRD  
RUGGEDIZATION DEC PT

FRAME  
MECH  
DESIGN

FAN FRAME FABRICATION  
(FST HARDWARE)

VANE  
STATIC  
TESTS

BENCH  
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INTERIM DESIGN REVIEW

DECISION DATE

PRELIMINARY  
DESIGN REVIEW

DETAIL DESIGN REVIEW

LEGEND :

FILE 302.1.ERC.06090.2/

REV DATE 10-16-81

WBS MGR Robert O. Colman 9/10/81

E3 APPROVAL 11/14/81 9/10/81

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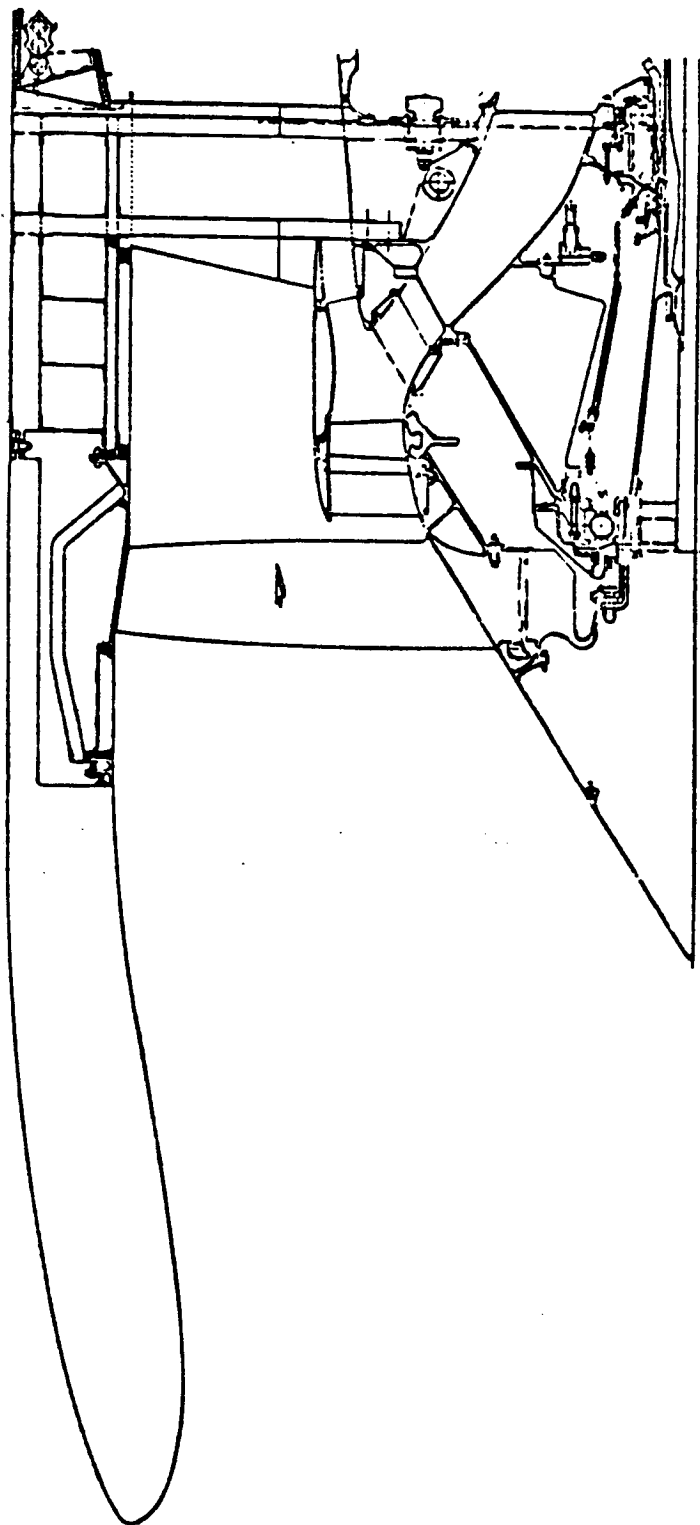


Figure 2.1.1-1. Fan Module Cross Section.

to the fan Detail Design Review (DDR) in February 1980; design parameters are shown in Table 2.1-I. Concurrent with the above effort, the final aerodynamic design of the frame structures was also completed during the last quarter of 1979. The final frame mechanical design was initiated at the beginning of 1979 and conducted during the latter part of 1979. The slave frame design was reviewed in an informal IDR on September 12, 1979 to allow an early start on the relatively long procurement cycle of the slave frame. Fabrication of the slave frame was completed during the first quarter of 1981.

Fan rotor hardware and the slave frame were available to initiate the component test buildup by the end of the first quarter of 1981. Following the instrumentation and buildup cycle, the fan component test was initiated in late September 1981.

#### 2.1.1 Fan Aerodynamic Design

##### Technical Progress

The principal activity in this Semiannual reporting period has been centered around planning and preparing for the fan component test, now scheduled for September 1981.

During this period, the final version of the Instrumentation Plan was approved and issued as required by contract. This plan includes a description of the fan test vehicle as well as the Large Fan Test Facility (LFTF) located in Lynn, Massachusetts where the fan will be tested. The aerodynamic instrumentation is described in detail, specifying the location and type of sensor, and the associated performance calculations. The vehicle and facility instrumentation are also described in the instrumentation plan. A complete list of each instrument element as well as the instrumentation drawing is provided.

The final version of the Test Plan was also approved and issued during this period, as required by contract. The Test Plan outlines the five phases of testing as follows: Mechanical checkout, performance mapping, bypass ratio excursions, dynamic pressure and traverse data, and distortion testing. Performance goals are presented in pretest-predicted fan and quarter stage performance maps, which are consistent with the overall program objectives.

Table 2.1-1. Fan Aerodynamic Design Parameters.

Parameters	Maximum Climb 35,000 feet/Mach	Maximum Cruise 0.8/+18° F	Takeoff SLS/+27° F
Corrected Tip Speed, ft/sec	1350	1311	1198
Corrected Airflow, lbm/sec	1419	1396	1274
Flow/Annulus Area, lbm/sec-ft <sup>2</sup>	42.8	42.1	38.4
Bypass Stream Pressure Ratio	1.65	1.61	1.50
Bypass Stream Adiabatic Efficiency, percent	87.9	88.7	90.0
Core Stream Pressure Ratio	1.67	1.63	1.51
Core Stream Adiabatic Efficiency, percent	88.5	89.2	89.7
Bypass Ratio	6.8	6.9	7.3

A data reduction plan has been formulated which specifies performance calculations required to best analyze the fan test results and how these calculations are handled in the centralized data reduction computer program. In addition to overall bypass and core stream performance, vane-mounted and traverse instrumentation will be used to measure the individual blade-row performance. Numerous wall static pressures, and boundary-layer rakes will be used to analyze the flow properties near the wall boundaries and to aid in the calculation of the flow at the bellmouth, bypass, core, and booster measuring planes. Dynamic and steady-state pressures over the fan rotor blade tip will be recorded for several data points and will be used to determine the shock structure of the flow in the rotor tip blade passage. Aerodynamic calibration of the individual rake and vane-mounted sensors has been incorporated into the main data-reduction computer program.

All necessary data reduction requirements have been specified to the Lynn computer programming personnel in order that the centralized data-reduction computer program can be satisfactorily modified for the fan test.

#### Work Planned

Test Coverage, data analysis, and reporting will be provided by fan aero personnel on the fan vehicle which is scheduled to begin test in September 1981.

#### 2.1.2 Fan Rotor Mechanical Design

##### 2.1.2.1 Fan Rig Rotor Mechanical Design

#### Technical Progress

The fan vehicle has been trail assembled and clearance checks have been taken. All clearances measured within assembly tolerances. The vehicle is undergoing final assembly prior to test initiation.

#### Work Planned

Follow remaining vehicle buildup and the subsequent test program.

#### 2.1.2.2 ICLS Fan Rotor

##### Technical Progress

Manufacturing has been started on the forward fan shaft and is progressing on schedule.

##### Work Planned

- Follow hardware procurement.
- Issue the ICLS fan rotor assembly drawing.

#### 2.1.3 Fan Stator Mechanical Design

##### 2.1.3.1 Frame Interface Design

##### Technical Progress

Interface requirements for all the ICLS hardware required were finalized during this reporting period. The configurations for the service line extension, extension support, oil-tube and retainer, and the gearbox mounting adaptor were identified in conjunction with the gearbox radial driveshaft, the gearbox mounting arrangement to the frame, and the service line collector box inside the core cowl. Following agreement between Test Facility Engineering and Design Engineering regarding the overall engine mount arrangement, the details of the machining required to the fan frame to accommodate the engine mount brackets, the gearbox brackets, and to perform the radial driveshaft alignment procedure have been defined. The definition of the ICLS interface requirements has allowed completion of the detail drawings and initiation of the hardware procurement.

Support for the assembly of the fan stator for the FSFT vehicle was provided during this period. The assembly was completed in early June and the vehicle shipped to Lynn. Data was also prepared to safety monitor the fan stator hardware during the fan test program. The full-scale fan test program was initiated at Lynn in late September.

#### Work Planned

- Provide safety monitoring support for testing of the full-scale fan vehicle.
- Support ICLS hardware fabrication.

#### 2.1.3.5 Frame Mechanical Design

#### Technical Progress

Detail drawings have been completed for the hardware required for the ICLS engine. This includes the bottom vane service line extension, extension support bracket, radial driveshaft oil tube and pilot bracket, gearbox and engine mount brackets, and nacelle cowl door seal rings. Additionally, design changes were also incorporated into the fan frame machining drawing. The aft face of the fan frame hub will have pockets and locating holes machined to position the engine mount brackets. Machining of the frame hub will also be required to provide an additional oils scavenge line through the core frame and to establish a true centerline at the compressor flange interface. Machining will also be required at the outer bypass case to accommodate the gearbox brackets and the radial driveshaft adaptor bracket. The adaptor bracket will be positioned on the frame to provide positive alignment of the radial driveshaft to the frame. Design work remaining to be completed is the acoustic panel design for the splitter island and the ICLS assembly drawings which should be accomplished before the end of the year.

#### Work Planned

- Complete the splitter acoustic panel design and the ICLS assembly drawings for the fan stator hardware.

#### 2.1.5 Fan Stator Design Testing

#### Technical Progress

A check of the strain gages for the fan stator vanes was performed during the vehicle assembly to verify the vane frequencies and the engine gage

response. This data was used in conjunction with the static bench test results to establish safety monitoring limits for the vanes during the full-scale fan test. The execution of this task completed the fan stator design testing.

#### Work Planned

None.

### 2.1.6 Full-Scale Fan Testing

#### 2.1.6.1 Component Development and Evaluation

##### Technical Progress

Engineering direction was provided for the instrumentation and assembly of the fan vehicle hardware. Preparation of a detailed instrumentation list and drawing for the fan vehicle was completed. Specified requirements for test facility control room display was completed and vehicle operational and mechanical instrumentation was recorded. Preparing and issuing of fan vehicle test request was completed. Engineering direction was provided at Lynn for the installation of the fan vehicle hardware into the test facility and for the termination of vehicle aerodynamic and mechanical instrumentation. Engineering direction was also provided for the initial fan performance testing activity.

#### Work Planned

- Provide engineering direction at Lynn for the remaining aerodynamic performance testing of the fan vehicle.
- Provide engineering direction for the removal of the fan vehicle hardware from the Lynn test facility.

#### 2.1.6.2 Evendale Test Facilities Engineering

##### Technical Progress

Completed fabrication of the fan inlet distortion screen hardware. Engineering support was provided during the assembly of the fan vehicle hardware

and the trial fitting of the slave adapting discharge hardware provided by TFE. Engineering support was also provided during installation of the slave adapting discharge hardware in the Lynn test facility and during the initial fan vehicle performance testing activity.

#### Work Planned

- Provide engineering support during the remaining fan vehicle aerodynamic performance testing to help resolve any problems that may arise.

#### 2.1.6.3 Instrumentation Design

##### Technical Progress

Engineering support was provided for the application of aerodynamic and mechanical instrumentation sensors to the various components of the fan vehicle. Engineering support was also provided during the fabrication of all aerodynamic instrumentation rakes and probes. Vibration sensors and dynamic pressure sensors were provided for installation on the fan hardware. Supported the instrumentation activities occurring at Lynn during the installation of the instrumented fan hardware into the test facility. Provided instrumentation design engineering personnel for monitoring of the rake stresses during the initial phases of the fan vehicle performance testing.

#### Work Planned

- Provide engineering support for the installation of traverse probe and dynamic pressure instrumentation into the fan vehicle.
- Provide engineering support for the monitoring of rake stresses during the remaining fan vehicle performance testing.

#### 2.1.6.4 Test Facilities Engineering - Lynn

##### Technical Progress

Completed installation of the new hydraulic actuation system for the bypass discharge valve operation and control. Completed checkout of bypass

discharge valve operation using the new electronic control system and verified the control setting accuracy and fast open response time. Completed repair and checkout of inlet pressure control valve. Disassembled the test facility gearbox and replaced high speed gears used on previous test vehicle with those required for fan vehicle testing. A no-load checkout run was completed after the drive gears were replaced. Engineering support was provided during disassembly and reassembly of the test facility slave aft frame hardware after replacement of roller bearings damaged during previous vehicle testing. Engineering support was also provided during installation of the fan vehicle hardware in the test facility and during the initial fan vehicle testing activity.

#### Work Planned

- Provide engineering support during the remaining fan vehicle testing to troubleshoot any test facility problems should they arise.
- Provide engineering support during removal of the fan vehicle hardware from the test facility.

#### 2.1.6.5 Development Assembly

#### Technical Progress

Completed fabrication of all fan vehicle assembly and balance tooling. Completed preparation and publication of fan vehicle assembly and balance procedures. Buildup and balance of the fan rotor subassembly was completed. Buildup of the fan frame subassembly was completed and the fan rotating hardware was installed to the fan frame to check axial and radial clearances between the rotating and stationary fan hardware. Various pieces of the TFE supplied slave adapting hardware was trial fitted to the fan vehicle hardware to ensure proper fitup when later installed in the Lynn test facility. All fan assembly work was completed and the fan vehicle hardware was shipped to Lynn on June 8, 1981.

#### Work Planned

- No further activity planned.

#### 2.1.6.6 Instrumentation Application

##### Technical Progress

Application of the required aerodynamic and mechanical instrumentation sensors to the fan vehicle hardware was completed. Fabrication of all aerodynamic rakes and probes was also completed. Instrumentation application shop manpower coverage was provided during assembly of the instrumented fan vehicle hardware.

##### Work Planned

- No further activity planned.

#### 2.1.6.7 Lynn Testing

##### Technical Progress

Completed removal of previous fan test vehicle from fan test facility. A failed roller bearing was found in the slave aft frame sump after removal of the slave aft frame from the facility exhaust plenum. The sump was removed from the slave aft frame and the failed roller bearing was replaced. New bypass discharge valve vanes were installed in the slave aft frame along with new actuation hardware required for the new hydraulic actuation system to be used for the bypass discharge valve. The slave aft frame was reinstalled to the facility exhaust plenum and assembly of the slave adapting hardware to the aft frame was completed. Installation of the fan frame to the slave adapting hardware was completed and the fan shaft and rotor spool were installed into the fan frame and mated to the test facility shafting. The remaining fan vehicle hardware was installed and instrumentation termination was completed. All lube and air services were connected and all test preparations were completed. Fan vehicle testing was initiated on September 21, 1981. A total of 23.75 hours of fan testing was completed by the end of this reporting period.

##### Work Planned

- Complete aerodynamic performance testing of fan vehicle.
- Complete removal of fan vehicle hardware from test facility and return hardware to Evendale.

## 2.1.7 Fan Fabrication

### 2.1.7.2 Fan Stator

#### Technical Progress

The fabrication of the fan stator hardware for the full-scale fan test (FSFT) was completed. The hardware was then instrumented and assembled to the vehicle. Figures 2.1-2 and 2.1-3 show the instrumented and assembled core frame to bypass vane assembly. Figures 2.1-4 and 2.1-5 show the core OGV assembly and the island splitter less the Stage 1 vanes and flowpath panels. Figure 2.1-6 shows the fan containment case which was modified from an existing production containment ring by wooden inserts. The fan blade tip rub material is shown between the two wooden panel sections.

With the completion of the hardware fabrication for the FSFT, orders have been placed for the hardware required for the ICLS engine test. Hardware to be procured includes the engine mount and gearbox brackets, nacelle cowl door seal rings, and the bottom bypass vane hardware, service line extension and stiffeners, support brackets, and the radial driveshaft oil tube and pilot bracket. The gearbox brackets and the oil tube and pilot bracket have been procured. The other hardware is on order and delivery is planned for the end of the year for all except the cowl door seal rings which should be completed in the first quarter of 1982.

#### Work Planned

- Monitor the manufacture of the ICLS hardware.

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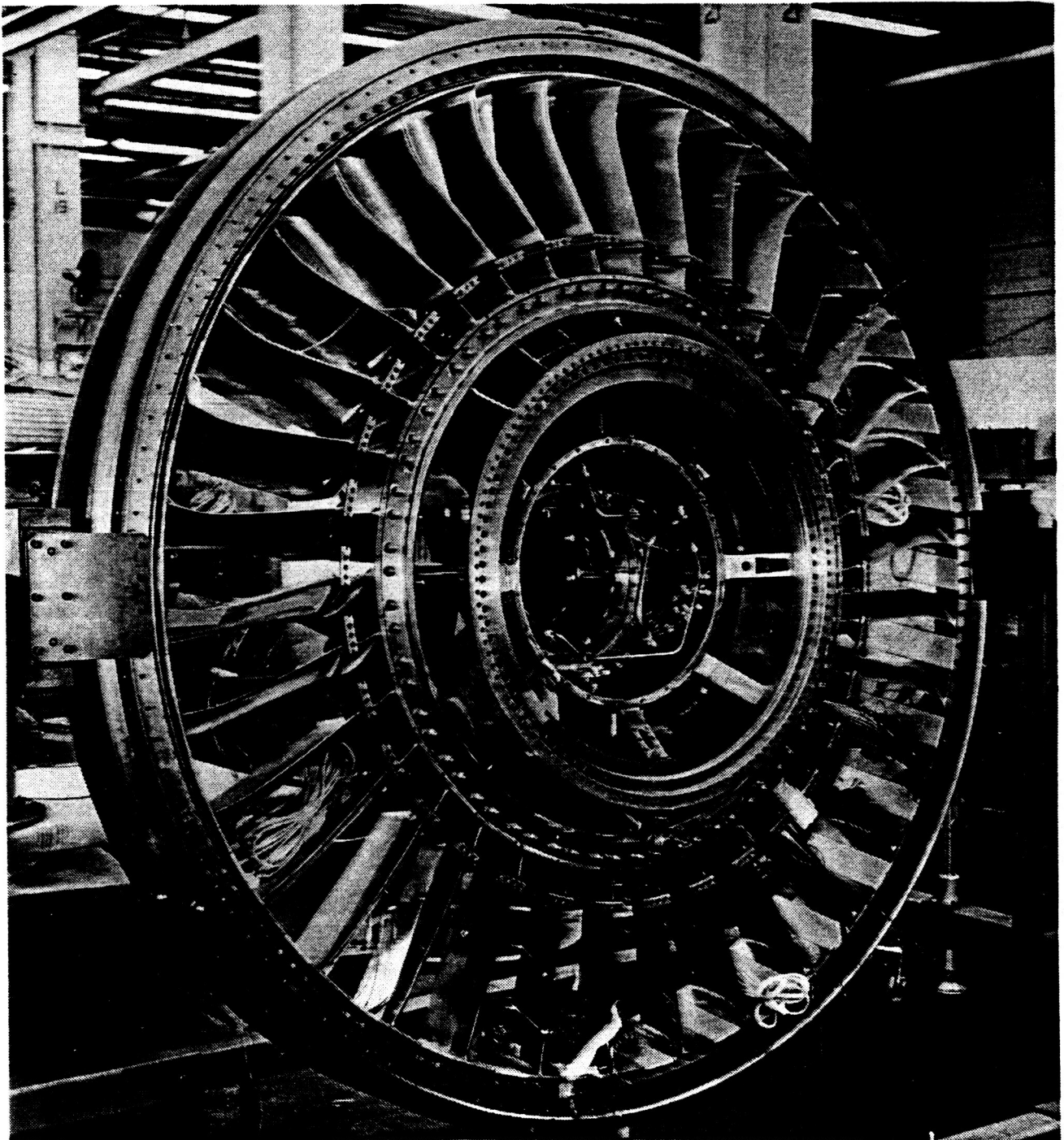


Figure 2.1-2. Core and Bypass Frame Assembly (Forward Side).

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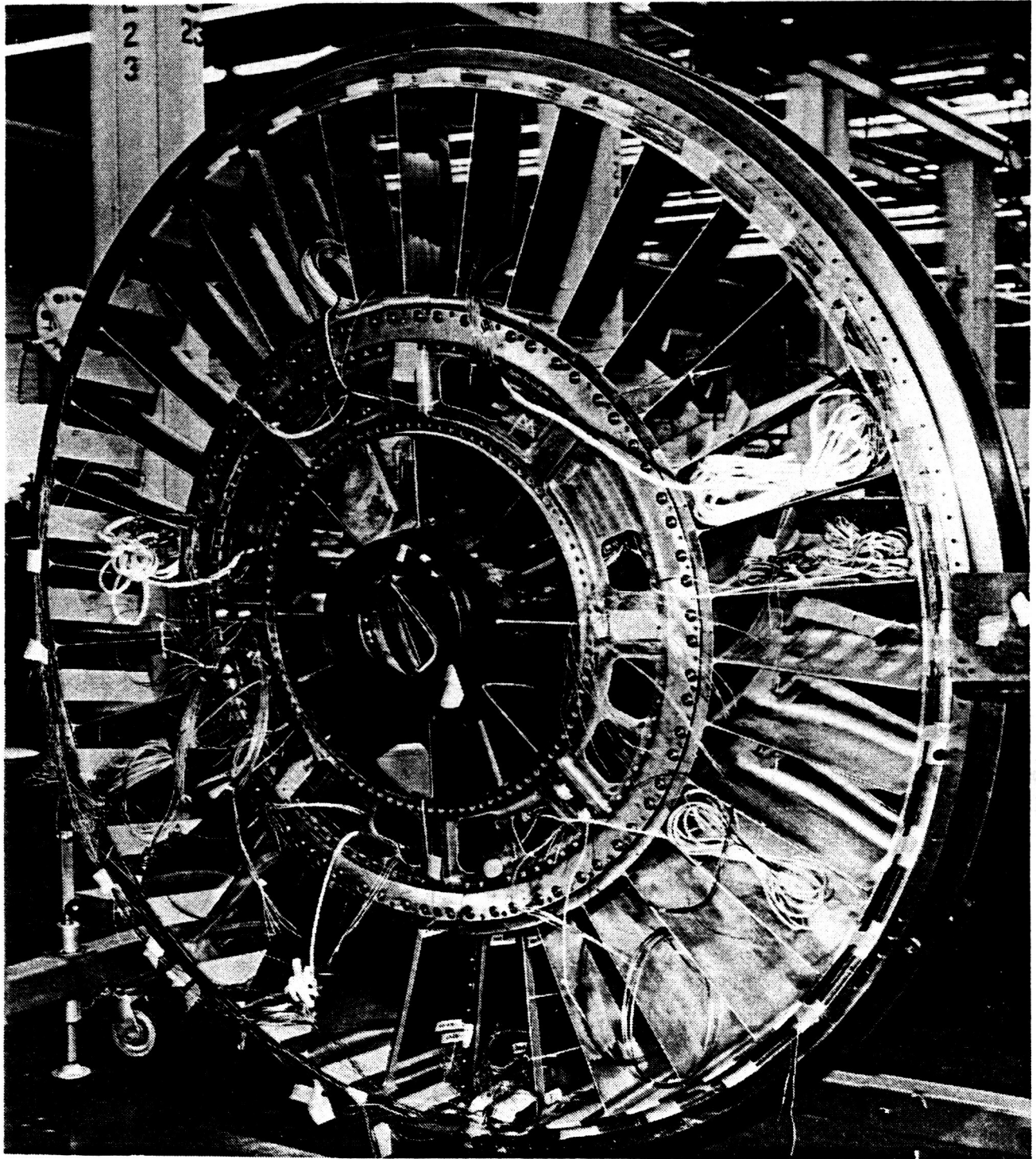


Figure 2.1-3. Core and Bypass Frame Assembly (Aft Side).

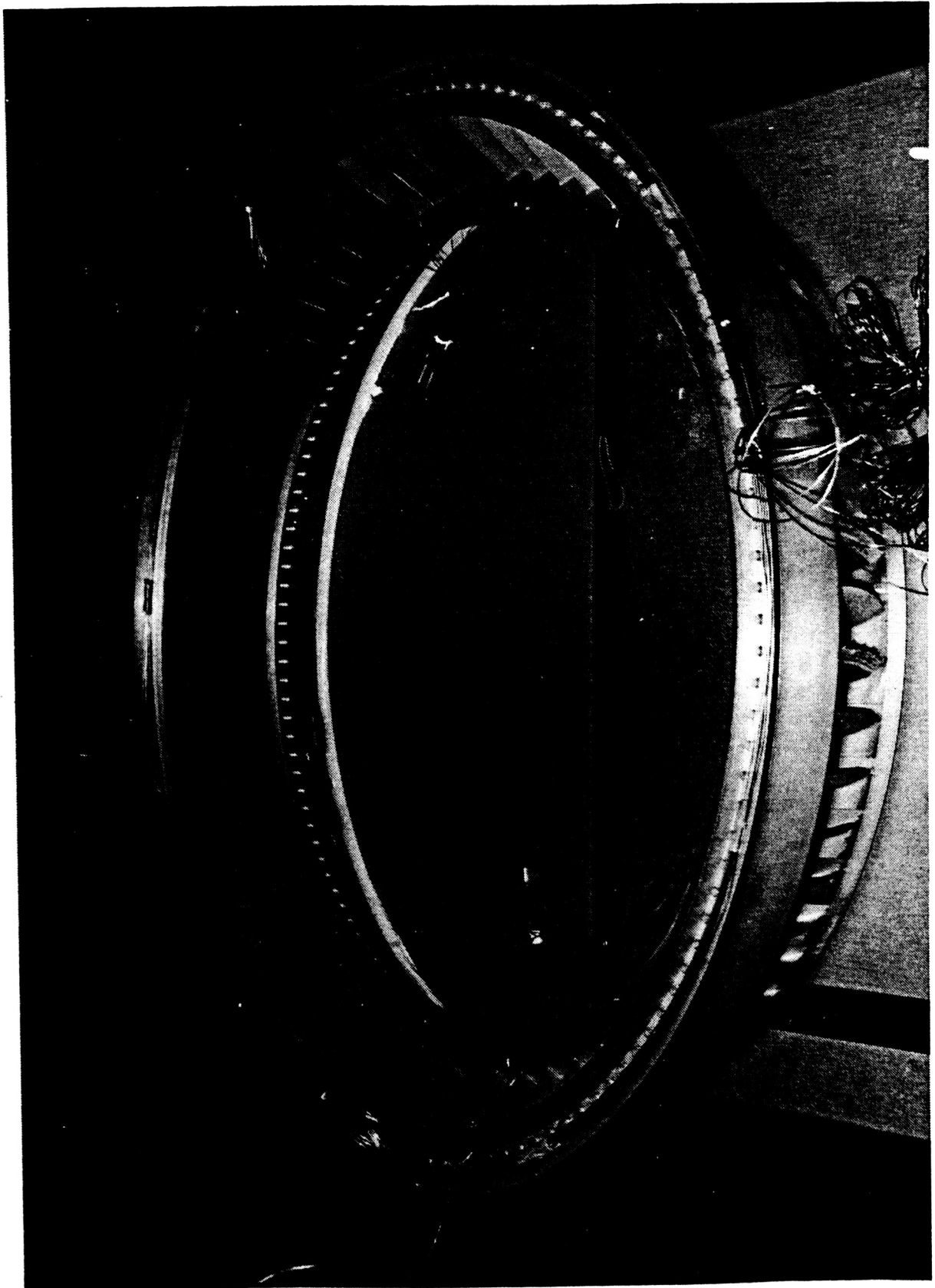


Figure 2.1-4. Core OGV Assembly.

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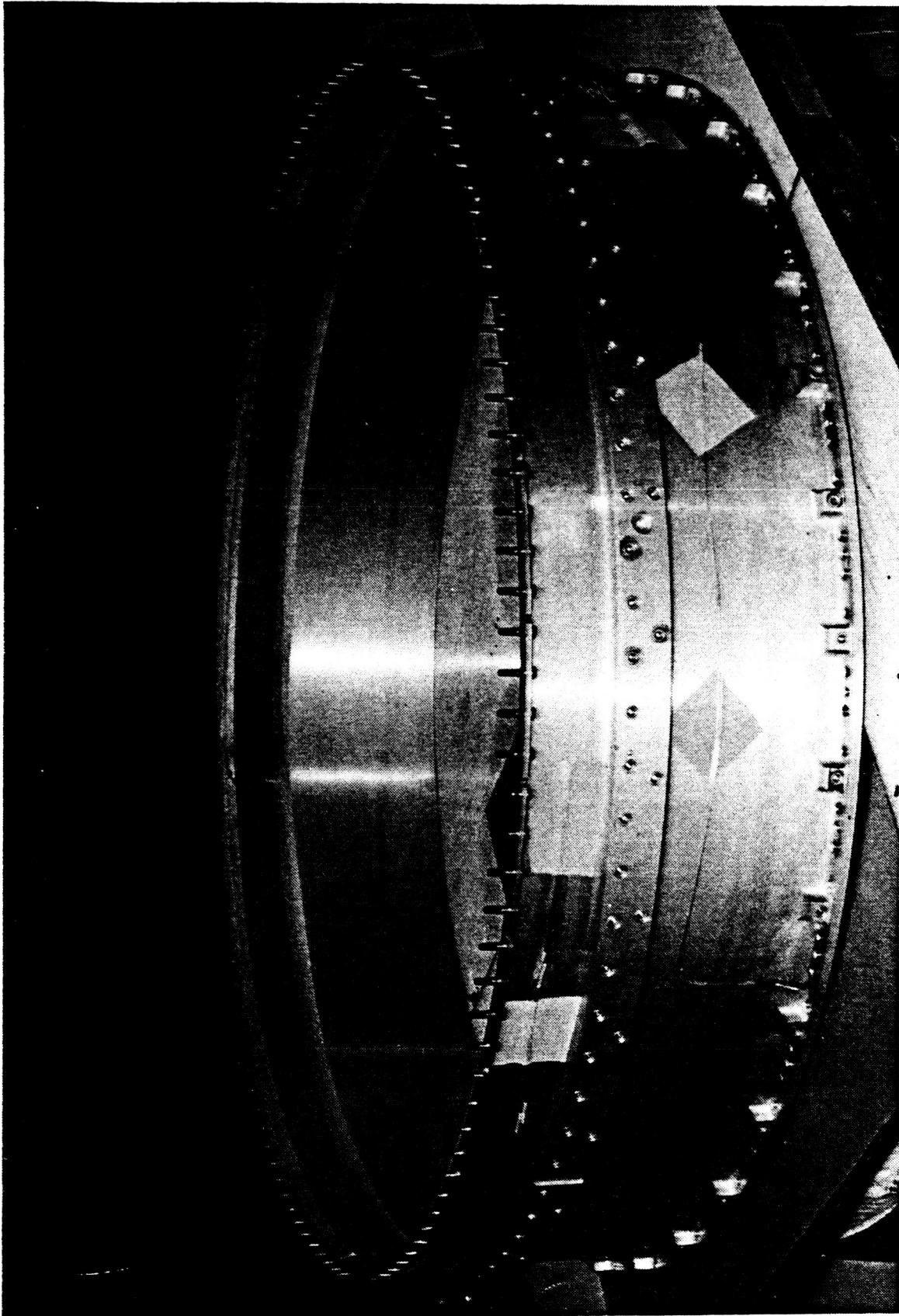


Figure 2.1-5. Stage 1 Vane Assembly Island.

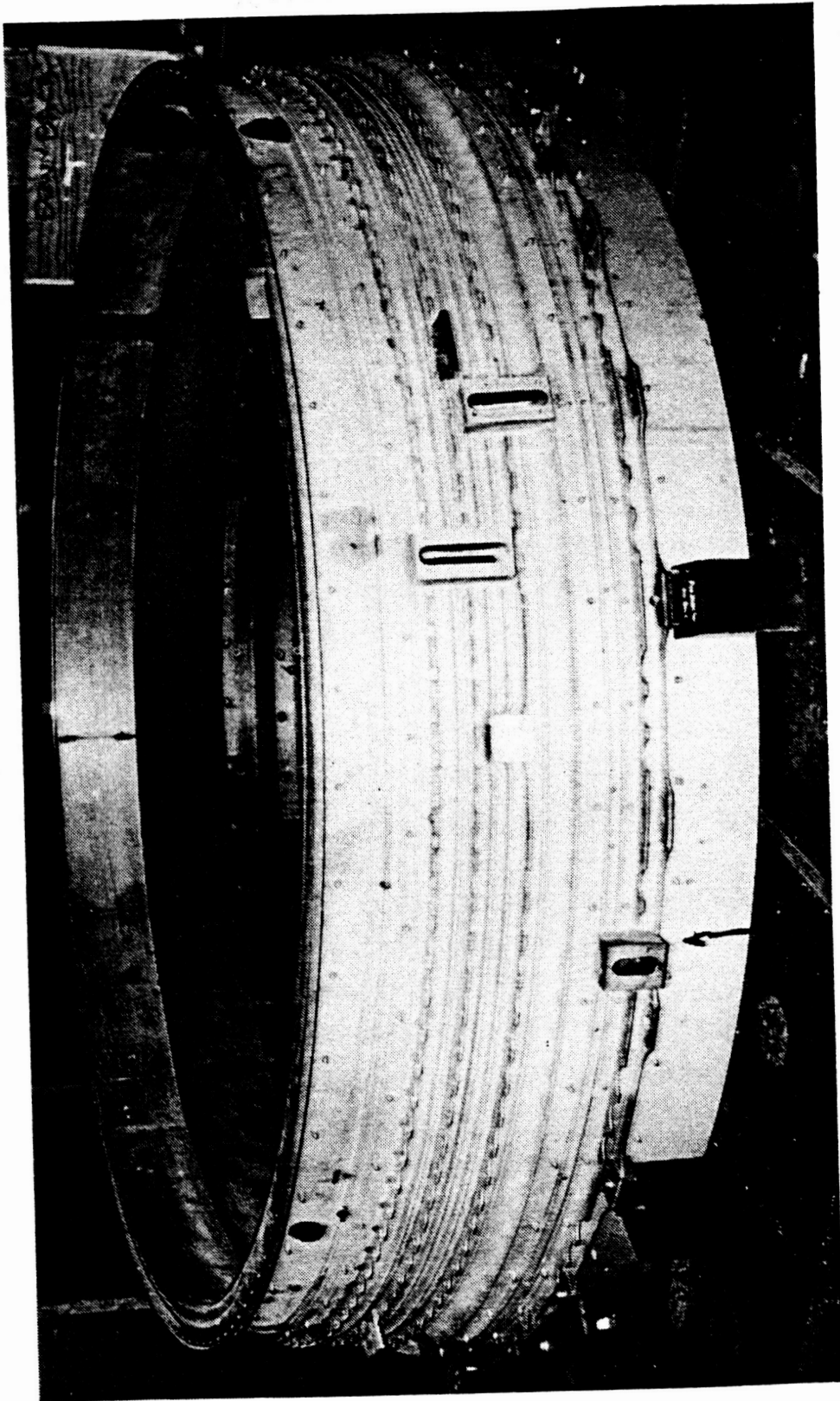


Figure 2.1-6. Fan Containment Case.

## 2.2 HIGH PRESSURE COMPRESSOR

### Overall Objectives

The primary objective of the compressor development effort is to evolve a 10-stage, high-performance, high-stage-loading design (Figure 2.2-1) capable of achieving a pressure ratio of 23:1 at the maximum climb design point. The primary aerodynamic design challenge is to provide adequate levels of stall margin at part-speed operation while maintaining the high efficiency levels required for this compressor. The FPS compressor efficiency goal is 0.861 at Mach 0.8, 35,000 feet, standard day, maximum cruise power setting.

The mechanical design requirements include the development of an active clearance-control system for the rear block of compressor stages to achieve tip clearances at cruise compatible with efficiency and stall margin goals and to enhance performance retention. The compressor has fewer, longer chord airfoils (low aspect ratio) to increase blade and vane life and general ruggedness and to reduce performance deterioration and operational costs. The compressor is short and stiff and, in conjunction with the short combustor and high pressure turbine, permits the use of only two bearings to support the core rotor.

A sequential arrangement of the tests will allow refinements of the design to be introduced throughout the compressor development test program. The test program will culminate with the ICLS test in 1982.

### Development Approach

Precontract aerodynamic design studies were completed in sufficient detail to allow the detailed aerodynamic design to commence at contract initiation. The initial contract efforts were devoted to the detail design and testing of the first six stages of the compressor. The PDR for the compressor was, therefore, completed very early in the program (February 1978). An IDR was held in July 1978 before committing to the hardware fabrication cycle for a 1-6 stage component test shown in Figure 2.2-2. Following instrumentation and assembly, the 1-6 stage component test was completed during the month of February 1980, and posttest analysis of the data has been completed.

**2.2 HIGH PRESSURE COMPRESSOR**  
R. BLACY

DATES SHOWN = 6 WEEKS

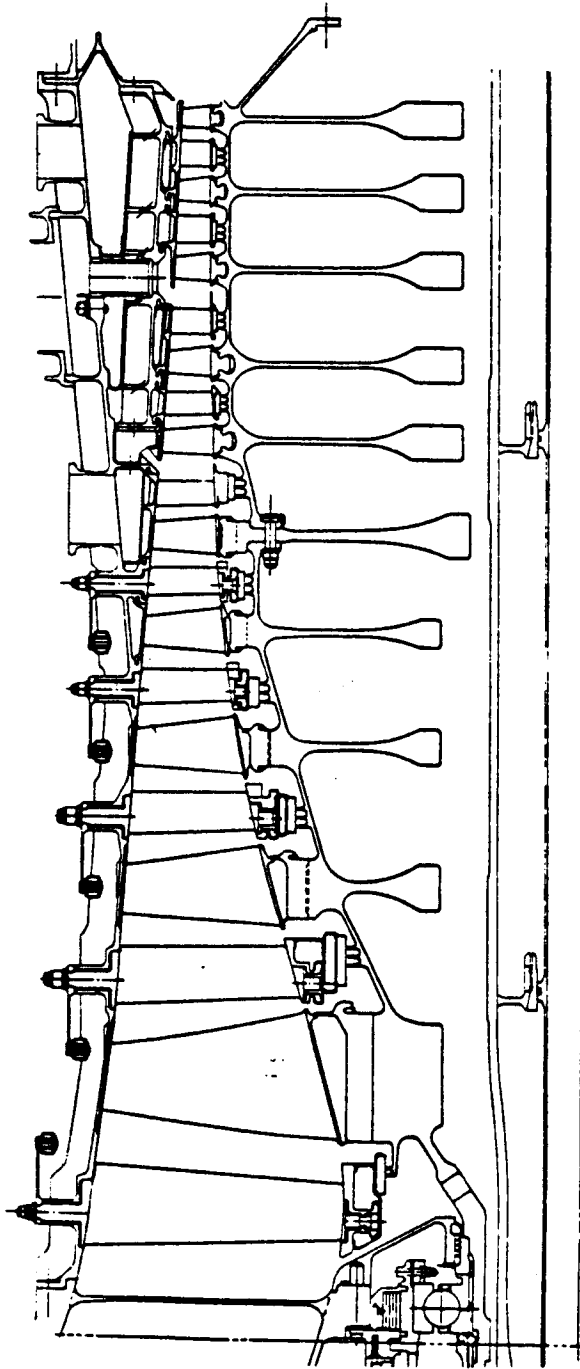
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- ▼ INTERIM DESIGN REVIEW
- ◆ DECISION DATE
- ▼ PRELIMINARY DESIGN REVIEW
- DETAIL DESIGN REVIEW

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**REV DATE:** 10-10-91  
**WBS MGR:** Robert P. Blacy  
**APPROVAL:** [Signature] 11/1/91

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- Efficiency - MXCR - 86.1%
- 10 Stage, 23:1 PR-MXCL
- Low Aspect Ratio, Rugged Blades
- Steel Casing
- Inertial Welded Spools
- T1 17 Forward, R95 Aft Spool
- Digital Control of Variable Stators
- Active Clearance Control Stages 6-10
- Adequate Stall Margin

Figure 2.2-1. HP Compressor Cross Section.

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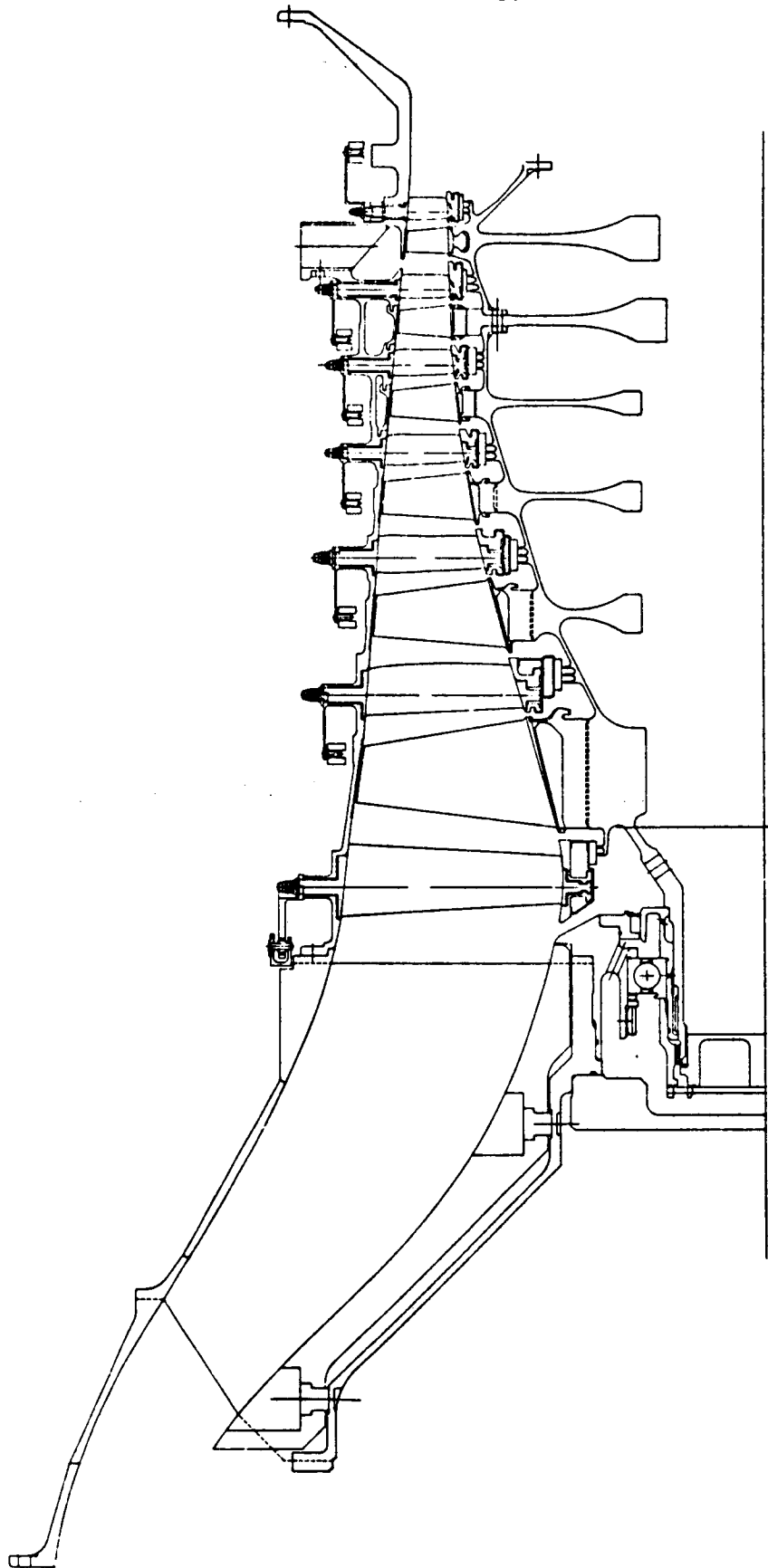


Figure 2.2-2. Stage 1 through 6 Compressor Rig.

The detailed aerodynamic and mechanical design of the rear stages of the compressor was completed in the first quarter of 1979 during the procurement cycle for the first six stages. This permitted an additional IDR for the entire 10-stage compressor in late January 1979; compressor aerodynamic design parameters are shown in Table 2.2-I. Upon successful completion of this IDR, the hardware for the last four stages of the compressor was released for procurement.

Appropriate hardware from the 1-6 stage vehicle was merged with the hardware procured for the aft stages to complete the 1-10 stage component buildup shown in Figure 2.2-3. The first 1-10 stage component test was completed during the first quarter of 1981.

Following analysis of the 10-stage test data, refinements in the mechanical and aerodynamic design were executed in the hardware for the second 10-stage component test in late 1981. Instrumentation of this hardware has been completed and assembly is in process.

A complete new set of hardware, refinements for which were defined based on the first 1-10 test, will be introduced into the first core engine test planned for the second quarter 1982. Upon successful completion of this test, the low pressure system will be added to the core and built up into the ICLS to be tested in late 1982.

### 2.2.1 Aerodynamic Design

#### 2.2.1.1 HPC Aero Component Design and Test

##### Technical Progress

The full 10-stage compressor was tested for the first time at the Lynn full-scale compressor test facility during March and April 1981. Tests were terminated because of foreign object damage before completing the entire scheduled test series, but a total of 10 runs were completed during which 199 steady-state data points and 35 intentional stalls were recorded. This was sufficient to determine overall performance characteristics with a near-optimum stator schedule. The effects of the Stage 5 customer bleed and

Table 2.2-I. Compressor Aerodynamic Design Parameters.

	Maximum Climb 35,000 ft/0.8 Mach/+18° F	Maximum Cruise	Takeoff SLS/+27° F
Corrected Speed, % Design	100.0	99.5	97.7
Corrected Airflow, lbm/sec	120.0	118.0	108.8
Total Pressure Ratio	23.0	22.4	20.0
Adiabatic Efficiency	0.857	0.861	0.865
Polytropic Efficiency	0.903	0.905	0.908
Inlet Temperature, ° R	547.9	542.5	621.6
Inlet Pressure, psia	8.65	8.42	21.84

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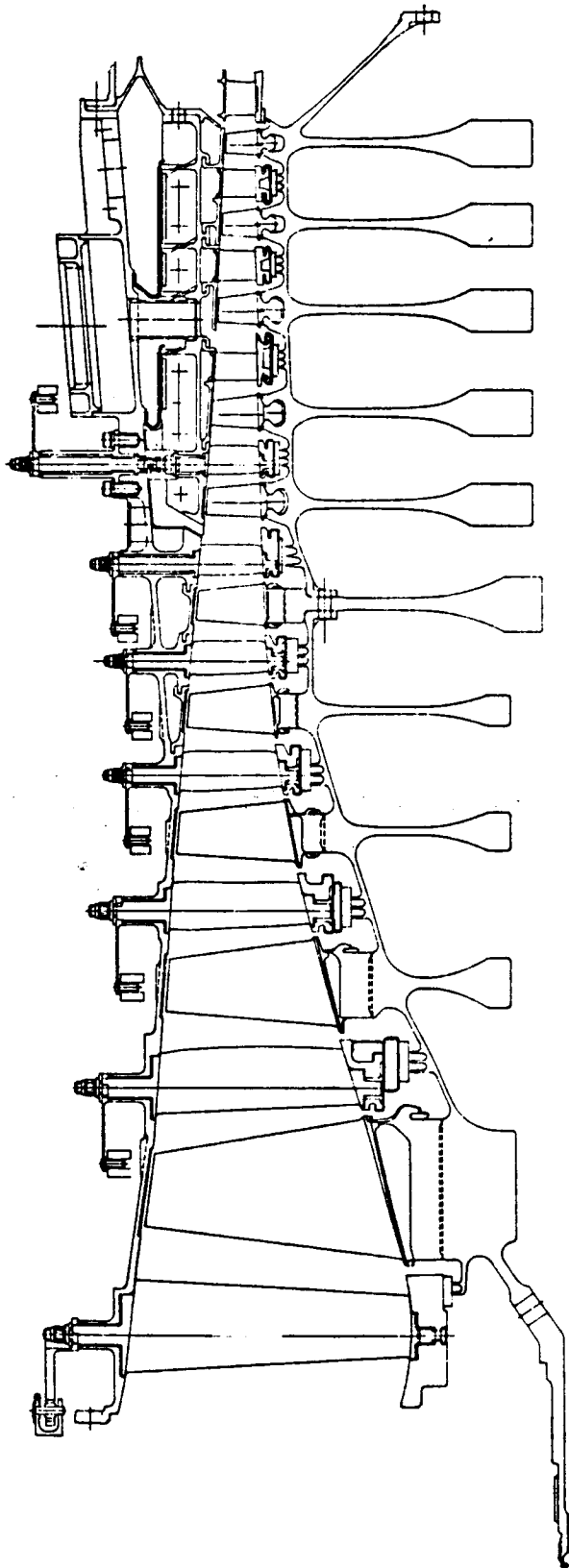


Figure 2.2-3. Stage 1 through 10 Compressor Rig.

Stage 7 starting bleed were also tested. In addition, the active clearance control and bore cooling flow systems were exercised near the FPS operating point.

The test results for this initial build of the full 10-stage compressor are summarized in the performance map shown in Figure 2.2-4. All the data points presented were taken without active clearance control case cooling and without either Stage 5 or Stage 7 bleed. At speeds of 87.5% and above, data were recorded under refrigerated and suppressed inlet conditions, for which the Reynolds number was low. The peak efficiency points shown for each speed were not adjusted for any unfavorable conditions of the test vehicle and environment. The design point pressure ratio of 23:1 and corrected flow of 120 lbm/sec were achieved at 97.5% speed. At this point the measured efficiency of 81.7% exceeded the goal for this test, as did the peak value of 82.6% measured near the cruise power setting. Adjustments totaling about 2 points in efficiency are believed to be appropriate to account for extensive instrumentation, low test Reynolds number, inlet duct loss bookkeeping, extra variable stator rows, and some hardware variances. The adjusted design point adiabatic efficiency of 83.7% is equivalent to a polytropic efficiency of 89.0%. The peak efficiency at each speed occurred about on the operating line.

The small margin above the FPS operating line was 11% at 97% flow and was 23% at 37% flow. The stall line was above the test objective at speeds of 80% or below and short of the objective at higher speeds. The peak efficiencies measured in the starting region were a few points above the objectives, and the stall margin in this subidle region was better than required for a rapid engine start without requiring either Stage 5 or Stage 7 bleed.

The detailed data analysis indicated that the front stator modifications and dovetail sealing that were incorporated after the six-stage test had worked better than expected; the hub region pressure ratio now equaled or exceeded the design intent. The high camber rear rotors likewise showed no sign of having weak hubs. Since the rear block in this build contained the original-design stators and the increased-camber rotors (about 6° more camber at all radii), the rear block pumping was considerably higher than

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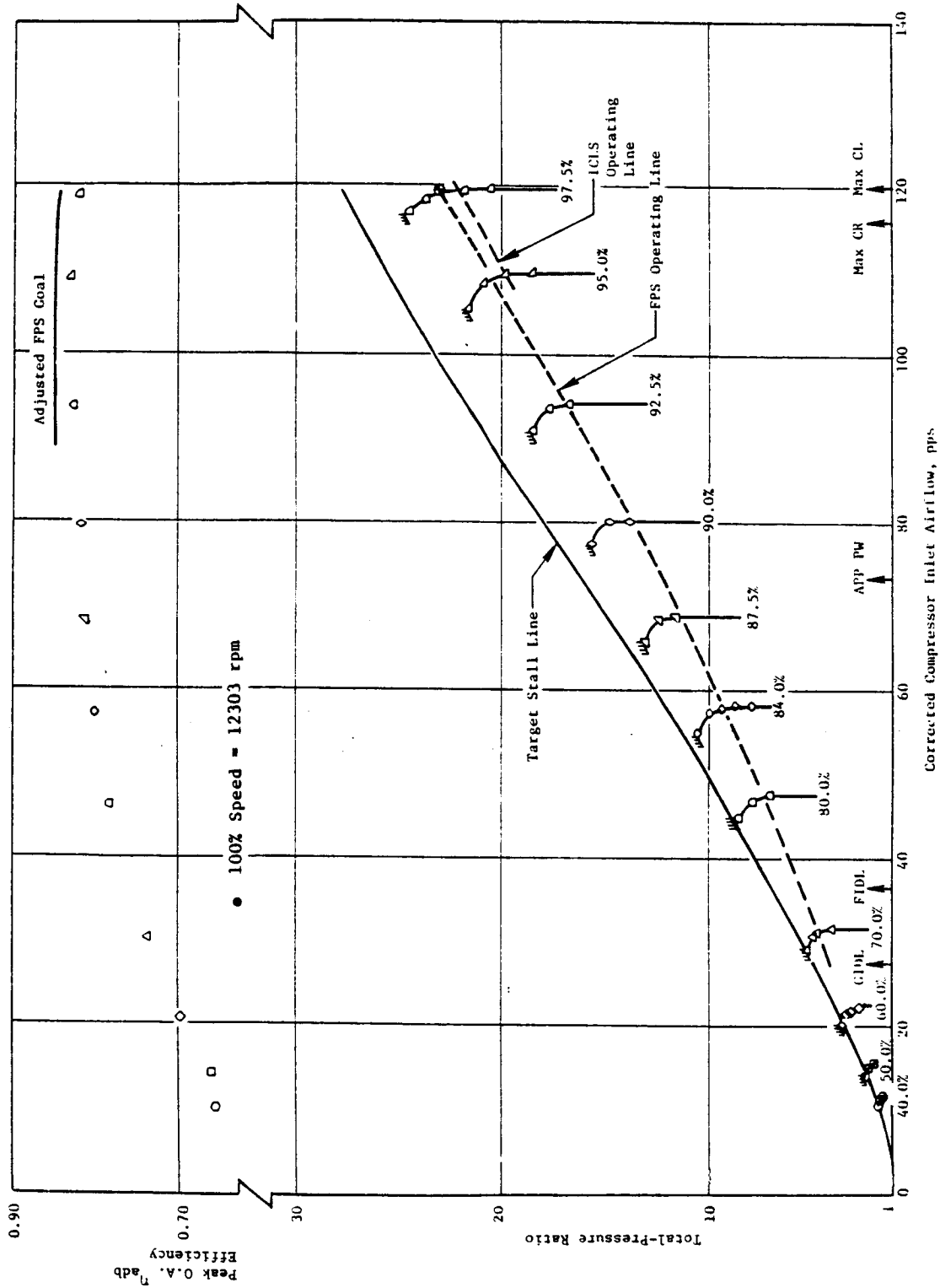


Figure 2.2-4. E<sup>3</sup> 10-Stage Compressor Test Map.

design intent. Therefore, it matched the compressor in such a way as to unload the front stages and to load up to the rear stages even though the front variable stators were set open from their design positions. This mismatching limited the stall margin at high speeds. The major need evident in the test results was to achieve a better balance between front and rear block pumping to improve high speed stall margin.

The interstage data indicated that peak efficiency of the front group of stages was not significantly better than demonstrated in the six-stage test, despite the large improvement in hub flow quality. Evidently twisting the stators open at their hubs raised losses due to stator hub incidence and rotor hub Mach number enough to offset any gains due to the reduction in hub diffusion factors and rotor hub incidence angles. In the rear stages, the peak efficiencies occurred below the operating line, and there was evidence that the flow was breaking down in the stators as the compressor was throttled. Analysis indicated that use of the redesigned front rotors and rear stators, as planned for future builds of the compressor, should reduce losses in these areas and give improve efficiency.

Based upon the above observations, the final compressor configuration for the core engine and ICLS turbofan engine will employ high hub camber Rotors 3 through 7 along with the twisted first rotor and original-design second rotor. The original Stators 2 through 5 and the opened-hub IGV, Stators 1 and 6, were selected. This group of stages was expected to have about the same pumping and hub strong pressure profile as the blading used in the first 10-stage build, but should have improved efficiency. The rear stages, for efficiency considerations, will employ redesigned high hub camber Stators 7 through 9 and the original-design OGV's. Rotors 8 through 10 will have the original airfoils, but will be staggered closed  $2^\circ$  at all radii in order to reduce the rear block pumping to its original design intent. This will achieve a better match with the front stages, and it was thus expected that high speed stall margin would be significantly improved. Although the low speed stall margin might be somewhat penalized, it was still expected to meet the requirements for a rapid engine start.

Performance estimates for this final configuration were made, using loss coefficients and deviation angles deduced from the first 10-stage

compressor test. This analysis indicated that the design airflow and 23:1 pressure ratio should be achieved at very close to 100% design speed. The predicted stagewise distribution of work input at the design point with the final blading was compared to the original design intent, and the differences were seen to be small. The vector diagrams of the final configuration were expected to be nearly as designed, except for some small differences near the hub.

Since the second full 10-stage compressor test was scheduled to be run in late 1981, the buildup schedule did not allow time for the newly defined rear Rotor 8 through 10 and the redesigned cast Stators 7 through 9 to be incorporated. As an acceptable alternative, the existing original-design rear rotors and stators were specified. This interim rear block was expected to produce about the same level pumping as the final configuration and thus would match well with the front stages. Its efficiency, however, was not anticipated to be significantly improved compared to the data from the first 10-stage test, since the original-design rear stators were thought to be the source of the higher-than-design losses.

Due to possible difficulties of casting the OGV-diffuser as an integrated ring for the ICLS turbofan engine, a backup design of the OGV was completed during this reporting period. The trailing edge thickness of the vane was increased 0.010 inches all across the span; the maximum and the leading edge thickness were increased about 0.007 inches. The pressure surface contour of the vane was kept unchanged while the additional thickness was applied to the suction surface. Calculated surface velocity distributions changed very little, however, so the performance impact of this change was expected to be insignificant.

Preparation for the second 10-stage test were carried out, and the aero definition of the instrumentation locations for the core engine compressor was also completed. Aero coverage of the 10-stage test vehicle buildup was provided to assure that hardware and instrumentation quality was consistent with the aero design intent.

### Work Planned

- The instrumentation plan and the test plan documentation will be prepared for the second full 10-stage compressor test.
- Data-acquisition/data reduction computer programs will be prepared for the second 10-stage test.
- The full-scale component test of the second build 10-stage core compressor will be run in late 1981.
- Preparation for the core engine and the ICLS turbofan engine tests will continue.

### 2.2.2 Rotor Mechanical Design

#### 2.2.2.1 Design of 1-6 Rig

#### Technical Progress

This effort has been completed and results have been integrated into the 1-10 rig tests.

### Work Planned

No further effort will be expended.

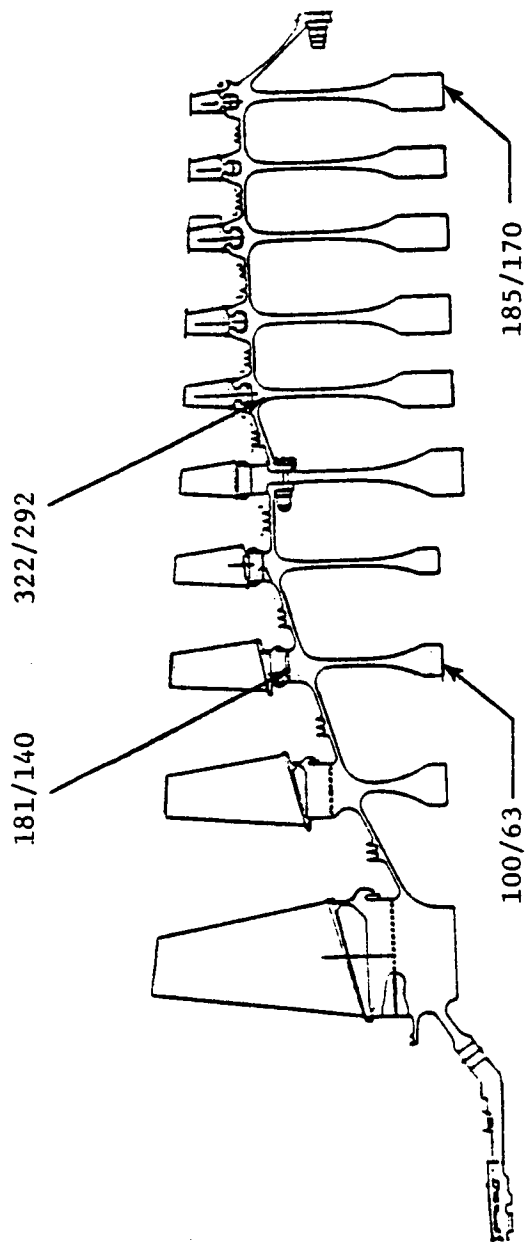
#### 2.2.2.2 Design of First 1-10 Rig

#### Technical Progress

During this reporting period, the first E<sup>3</sup> compressor rotor 1-10 rig design effort was completed. The effort during this period involved the completion of the rig component test in the General Electric Full-Scale Compressor Test facility in Lynn, Massachusetts, the disassembly of the rig vehicle components, posttest hardware inspection, analysis of the test data, and the submittal of a test memo documenting the mechanical results of the test. Observations relative to this test as follows:

- The rotor temperatures measured during the test indicated that all the stages ran hotter than predicted but the variance between actual and predicted decreased for the aft stages (see Figure 2.2-5). This decrease in variance in the aft region was influenced somewhat by the presence of the instrumentation lead out duct which runs

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	T <sub>25</sub> (°F)	P <sub>25</sub> (psia)	T <sub>3</sub> (°F)	N <sub>Phys</sub>	% N <sub>Corr.</sub>	T <sub>Bore Cool</sub> (°F)	W <sub>Bore Cool</sub> (lbm/sec)
Test Point Conditions	-67	3.81	611	10610	99	57	0.86
Prediction Point Conditions	-63	4.28	006	10764	100	60	0.86

Figure 2.2-5. Temperature Comparison - Measured/Predicted.

from the Stage 5 bore aft to the slave CDP seal disk. The effectiveness of the bore cooling flow is close to calculated levels and is shown in Figure 2.2-6.

- Correlation of actual versus predicted blade natural frequencies is well within the range of values expected from the blade-to-blade variation band.
- Blade steady-state vibratory stresses were below 35% of the established HCF limit with the exception of Stages 5, 6, and 7. These rotor stages were excited by a strong 1/rev stimulus resulting from a damaged Stage 6 vane with a reverse cambered trailing edge (see Section 2.2.3.2).
- Blade stall stresses are within expected values except for Stage 3 which had high speed stall stresses exceeding 200% limits. This blade has been redesigned for both the second 1-10 rig test and core engine test and should exhibit lower stresses during stall.
- The vehicle sustained an inadvertent long stall on 4/10/81 and borescope inspection revealed FOD on the leading edge of all of the blade stages (except 1 and 2 which were not inspected). Since the stator stages could only be inspected in the immediate area of the borescope ports and could possibly have suffered the same or more extensive damage, it was decided to remove the vehicle.
- After disassembly, the following damage was noted:
  - Three Stage 1 blades had tip tears.
  - One Stage 1 blade had a large, smooth deformation on the leading edge slightly above midspan.
  - All of the blade rows had leading edge nicks, with approximately 20% of the blades in Stages 6 through 10 exhibiting some damage.

The smooth leading edge deformation at midspan on the one Stage 1 blade had the appearance normally associated with soft-body impact. Based on this and the distribution/appearance of the remaining airfoil damage, it has been concluded that ice ingestion encountered during refrigerated inlet air testing caused the Stage 1 blade damage (both the leading edge dent and the tip tears), with the remaining airfoil damage caused by the passage of the Stage 1 fragmented blade tips. A damage report covering this event was prepared and submitted for approval. The general condition of the hardware was very good - the ice ingestion and sustained stall provided an accidental demonstration of the vehicle ruggedness.

- Rub patterns on the blade shrouds and posttest analytical calculations indicate that the front stages ran with larger clearances than desired and the aft stages ran with smaller clearances than desired.

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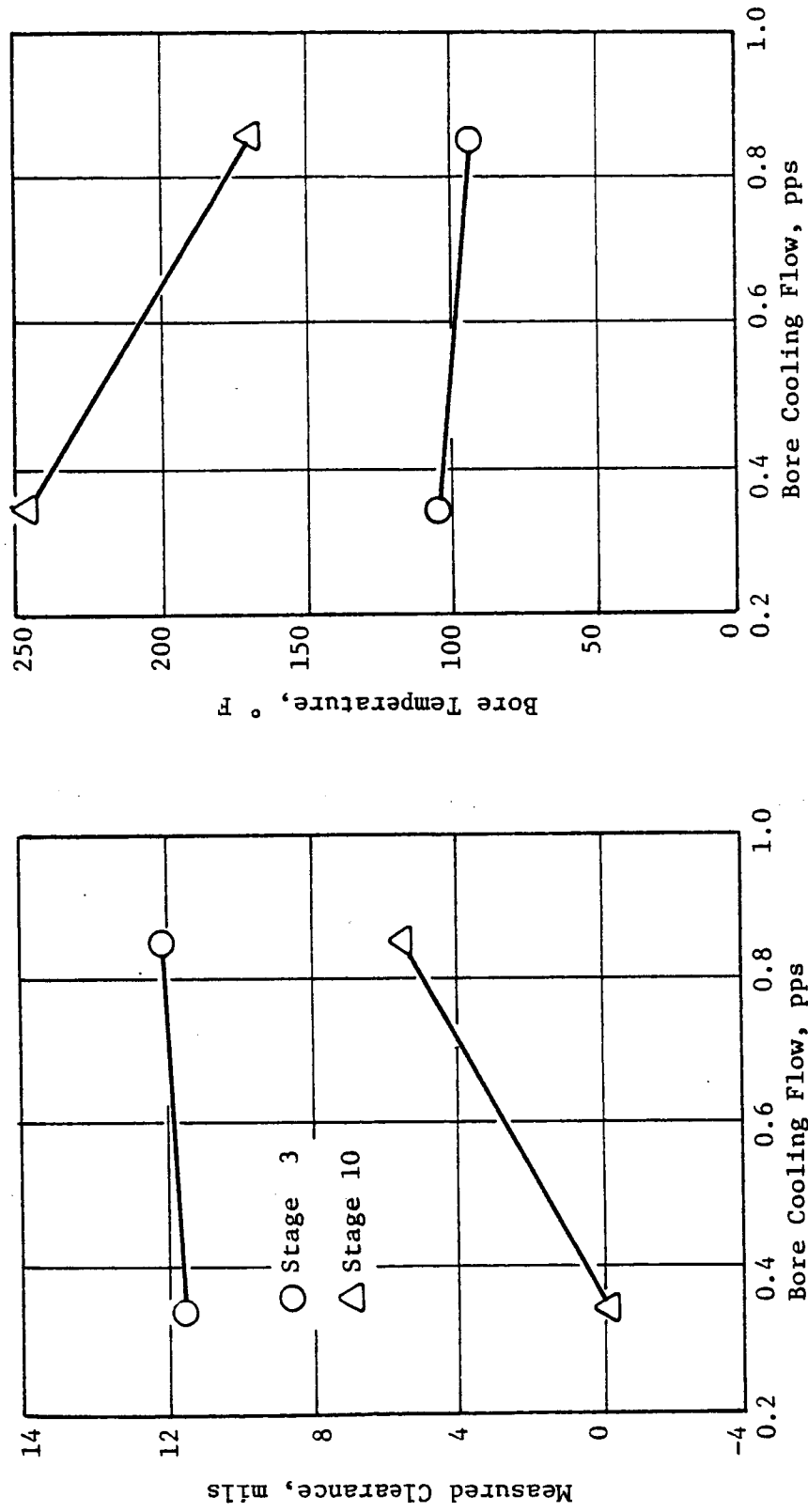


Figure 2.2-6. Effect on Bore Temperature and Blade Tip Clearance.

#### Work Planned

- This effort has been completed and no further effort will be expended.

#### 2.2.2.3 Design of Second 1-10 Rig

#### Technical Progress

Upon teardown of the rig vehicle following the first 1-10 rig test, work immediately commenced on the buildup of the vehicle for the second 1-10 rig test. After reviewing the aerodynamic data from the first rig test, it was decided to replace Stages 3 through 7 blades with the designs that will be used in the core and to replace Stages 8, 9, and 10 Mod B blades with the Mod A blades (which are more closed). The damaged Stage 1 and 2 blades have been replaced with spares. The rotor has been completely reassembled without breaking any of the bolt joints by splicing instrumentation leads to the new instrumented blades. The rotor has been high speed tip ground with radii values determined by updating rotor and stator deflections using measured test temperatures. The rotor has been balanced and is being installed into the frames in preparation for final vehicle assembly.

#### Work Planned

- Complete vehicle assembly and review clearance checks.
- Complete planned testing at the Lynn test facility.

#### 2.2.2.4 Design of Core HPC

#### Technical Progress

During this period, the E<sup>3</sup> core HPC design effort involved the following:

- First article inspection of the Stage 3, 4, and 7 blades has been completed.
- Released instrumentation rework drawings for the rotor spool components.
- Defined clearance criteria and established clearance values for the core engine limit clearance drawing.

- Identified modifications to the design and use of clearanceometers and touch probes to improve the accuracy of measured clearance data.
- Issued detail drawings for the Stage 8, 9, and 10 blades and released the order to the machining vendor. These Mod C blades are more closed than the Mod A blades.
- Supported initial dimensional checks and trial assembly of the available core rotor components.
- Supported instrumentation of the rotor blades.

#### Work Planned

- Support manufacturing and receive all remaining core rotor hardware.
- Support the instrumentation and assembly of the core rotor buildup.

### 2.2.3 Stator Mechanical Design

#### 2.2.3.2 Design of 1-10 Rig, Build I

#### Technical Progress

Engineering provided safety monitoring during the vehicle test. The test was cancelled when blade FOD was discovered during posttest borescoping after a long-duration stall. Maximum stator stresses observed during the test are summarized in the following table:

<u>Stage</u>	<u>Normalized Operation (% Limits)</u>	<u>Stall (% Limits)</u>
IGV	3	<40
1	7	<40
2	11	<40
3	4	<40
4	24	<40
5	30	<40
6	30	<40
7	30	<40
8	40	<40
9	56	<40
OGV	1F and 1T not excited	

Vane vibratory frequencies were comparable to those predicted by the analyses.

Visual inspections of the stator hardware after vehicle disassembly disclosed the following vane damage:

<u>Stage</u>	<u>Description of Damage</u>	<u>Number of Damaged Vanes</u>
IGV	Trailing Edge Nicks	1
1	Trailing Edge Nicks	2
2	Trailing Edge Nicks	1
3	Trailing Edge Nicks	4
4	Trailing Edge Nicks	3
5	Trailing Edge Nicks	11
6	Trailing Edge Nicks	9
7	Trailing Edge Nicks	2
8	Trailing Edge Nicks	6
9	Trailing Edge Nicks	2
OGV	Trailing Edge Nicks	7

In addition to the above damage, the trailing edge of one Stage 6 vane was found to be severely bent over one-third of the lower span (see Figure 2.2-7). The damage occurred during buildup and was the probable cause for the strange 1/rev excitation on Rotors 5, 6, and 7 (see Section 2.2.2.2) observed during test. The damaged vanes will either be replaced or repaired, as appropriate, for the 1-10 Build II test.

#### Work Planned

No further effort will be expended.

#### 2.2.3.3 Design of 1-10 Rig, Build II

##### Technical Progress

After completing analysis of the aero data from the first 1-10 test, the technical scope of the second 1-10 rig was revised. To better balance

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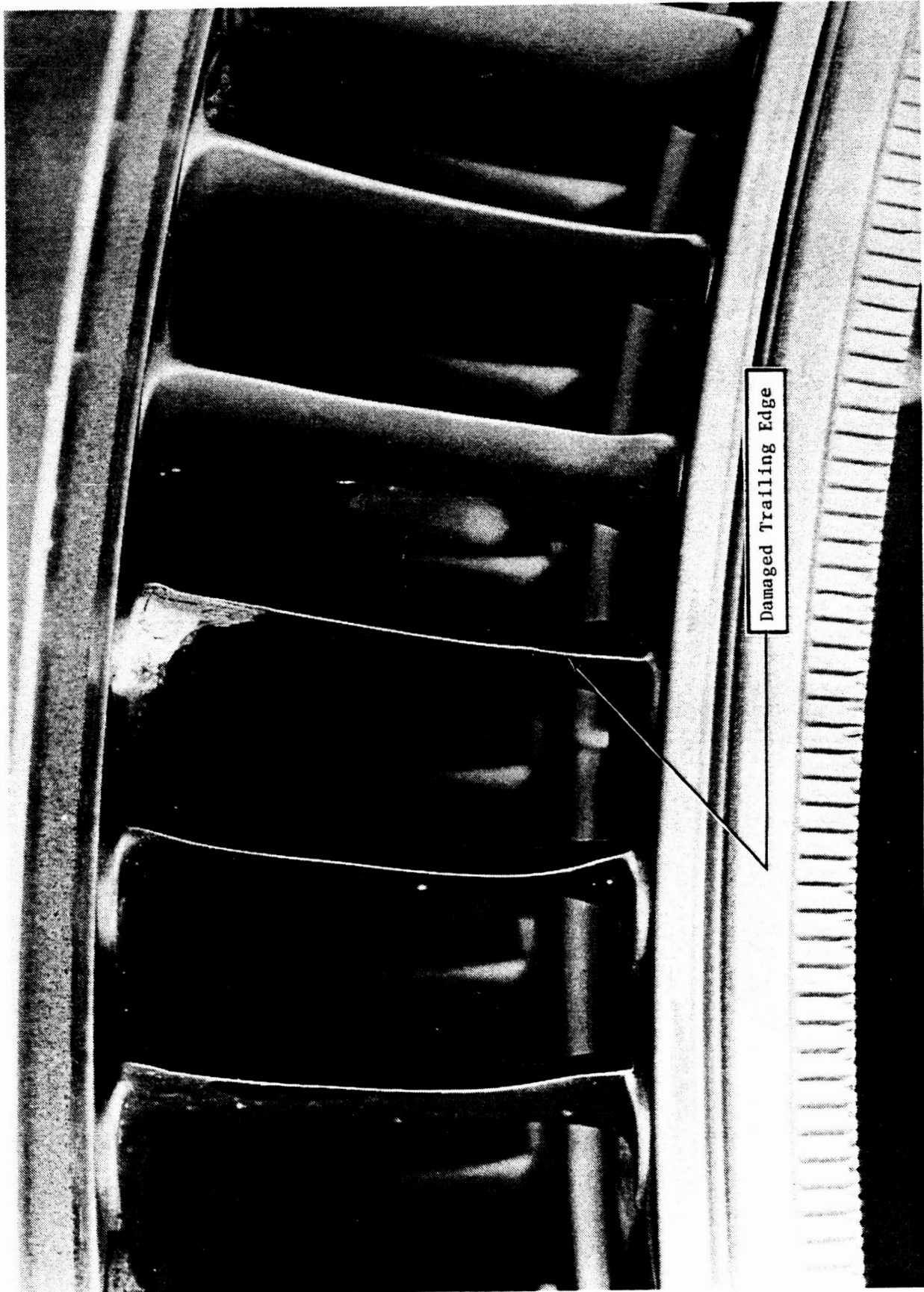


Figure 2.2-7. E<sup>3</sup> Stage 6 Stator Vanes 1-10A Posttest.

the front and rear block pumping, it was decided to recamber Stators 2 through 5 to the original design and to keep the remaining stator stages the same as the first 1-10 rig. Engineering support was provided during the vane rework.

Initiated engineering support of the Build II vehicle assembly.

#### Work Planned

- Continue to support the vehicle assembly.
- Provide safety monitoring during vehicle tests.
- Analyze test data and prepare summary of test results.

#### 2.2.3.4 Design of Core Engine

##### Technical Progress

Thermal, stress, and life analyses of the diffuser frame were completed. Thermal and stress computer models of the compressor structure were updated with the 1-10A test data.

Engineering support of the hardware procurement is continuing.

Initiated engineering support of the engine assembly.

#### Work Planned

- Calculate rotor/stator clearances.
- Complete support of hardware procurement.
- Continue support of engine assembly.

#### 2.2.3.5 Design of ICLS Engine

##### Technical Progress

Detail design and analysis of the VSV torsion bar actuation system was completed and the bulk of the drawings were issued. Initiated procurement of the hardware components.

#### Work Planned

- Continue support of hardware procurement.

#### 2.2.4 Rotor Design Testing

##### Technical Progress

Bench testing of the core compressor blades, consisting of determination of airfoil natural frequencies and nodal patterns, has been completed for all stages except for the Mod C Stage 8, 9, and 10 blades. The Mod C Stage 8, 9, and 10 blade redesign involved only a stagger angle change and therefore will not require further retest of vibrational characteristics. The Stage 3 blade has been completely redesigned and has gone through the entire gamut of bench tests, including the one measuring root fillet end effects. This completes all of the core rotor blade bench testing.

#### Work Planned

- Conduct an impulse vibration bench test of the core compressor rotor instrumentation lead out duct to verify analytical frequency predictions.

#### 2.2.6 Full-Scale Compressor Testing

##### 2.2.6.1 Component Development and Evaluation

##### Technical Progress

Provided engineering direction at Lynn for the five test runs performed on the 10A compressor vehicle between March 31 and April 10, 1981. Engineering direction was then provided for removal of the 10A compressor from the Lynn test facility and for the subsequent disassembly of the 10A compressor at Evendale. Planning efforts were completed to determine the work activity required to refurbish the 10A compressor vehicle hardware and instrumentation for use in the buildup of the 10B compressor vehicle. Engineering direction was provided for the instrumentation and assembly work required for buildup of the 10B compressor vehicle. Conducted an investigation on the cause of the rotor blade and stator vane damage incurred during testing of the 10A compressor vehicle. A damage report was written and published.

#### Work Planned

- Provide engineering direction to complete the buildup of the 10B compressor vehicle.
- Provide engineering direction at Lynn for the test cell installation of the 10B compressor.
- Provide engineering direction at Lynn for the aerodynamic performance testing of the 10B compressor.

#### 2.2.6.2 Test Facilities Engineering

##### Technical Progress

Engineering support was provided during the five test runs conducted on the 10A compressor vehicle at Lynn and during the subsequent disassembly activity on the 10A compressor at Evendale. All rotating and stationary TFE supplied slave hardware from the 10A compressor was inspected and all hardware was acceptable for use in the 10B compressor buildup. Engineering support was provided during buildup of the 10B compressor vehicle.

#### Work Planned

- Provide engineering support as required during the buildup, test cell installation, and testing of the 10B compressor vehicle.

#### 2.2.6.3 Instrumentation

##### 2.2.6.3.1 Instrumentation Application

##### Technical Progress

Support was provided by the instrumentation shop during disassembly of the 10A compressor vehicle. This film strain gage application was completed on the new Stage 3, 4, 5, 6, and 7 rotor blade airfoils. The instrumented rotor blades were installed in the rotor spool and splicing to the existing spool leadwire was completed. Installation of new aerodynamic sensors to Stage 2, 3, 4, and 5 stator vanes was completed. Checkout and repair of existing sensors on the IGV's, Stage 1 stator vanes, and forward stator were completed. Checkout and repair of sensors on the aft stator case and

fixed stator vane segments were completed. Checkout and repair of existing sensors of the front frame, diffuser frame, and rear frame were completed. A new Plane 3.1 diffuser exit aerodynamic rake was fabricated. Instrumentation shop support was provided during buildup of the various 10B compressor vehicle subassemblies.

#### Work Planned

- Provide instrumentation shop support during main vehicle buildup and final termination of aerodynamic and mechanical instrumentation prior to shipment of the vehicle to Lynn.

#### 2.2.6.3.2 Instrumentation Design

#### Technical Progress

Provide engineering support during test of 10A compressor and during subsequent disassembly of 10A compressor vehicle at Evendale. Reviewed posttest instrumentation sensor condition and investigate causes of instrumentation faults observed during the 10A compressor testing. Complete definition of instrumentation application and repair methods to be used on the new and existing vehicle hardware, respectively. Provided engineering support during the application and repair work performed in the instrumentation shop. Completed the aerodynamic calibration of the newly applied and repaired sensors on stator vanes in Stages 2, 3, 4, 5, 6, 7, 8, and 9. Completed definition of required changes to the clearanceometer and touch probe hardware and systems to improve the quality of the rotor blade tip clearance measurements during the 10B compressor test.

#### Work Planned

- Provide engineering support during the 10B compressor main vehicle buildup activity and final instrumentation termination.
- Provide engineering support during the 10B compressor test cell installation and testing phases.

#### 2.2.6.4 Development Assembly

##### Technical Progress

Completed disassembly of the 10A compressor vehicle into major subassemblies. Partially disassembled the forward compressor stator, aft compressor stator, and compressor rotor subassemblies in order to modify and replace existing hardware items. Completed buildup of compressor rotor system with new blades installed in Stages 3, 4, 5, 6, 7, 8, 9, and 10. Completed buildup of forward stator case subassembly with modified stator vanes installed in Stages 2, 3, 4, and 5. Completed buildup of aft stator case, diffuser frame, and front frame subassemblies. Initiated 10B compressor main vehicle buildup cycle.

##### Work Planned

- Complete assembly of 10B compressor vehicle and ship to Lynn.

#### 2.2.6.5 Lynn Testing

##### 2.2.6.5.1 Test Facilities Engineering-Lynn

##### Technical Progress

Provide engineering support during the remaining five test runs and during test cell removal of the 10A compressor vehicle. Initiated efforts to prepare the compressor test facility for testing the 10B compressor vehicle by modifying existing facility systems to improve their operation and capabilities for the 10B compressor vehicle.

##### Work Planned

- Complete modification to existing test facility systems.
- Provide engineering support during the test cell installation, testing, and test cell removal of the 10B compressor vehicle.

#### 2.2.6.5.3 Stage 1-10 Compressor Testing

##### Technical Progress

Additional performance testing was accomplished on the 10A compressor vehicle on March 31 and April 3, 8, 9, and 10, 1981. Testing was interrupted on April 10, 1981 when a severe vehicle stall was encountered. After shutdown, the compressor vehicle was borescoped and blade damage was observed on rotor Stages 6 through 10. Removal of the vehicle from the test facility was initiated on April 13 and the vehicle was shipped from Lynn on April 22, 1981. At the completion of the test run on April 10, 1981, a total of 79 hours and 57 minutes of testing had been completed and a total of 199 data points had been recorded. The compressor vehicle was stalled 46 times during the 10 test runs.

##### Work Planned

- Activity under this WBS has been completed.

#### 2.2.6.5.4 Stage 1-10 Compressor Testing

##### Technical Progress

Initiated program preparation efforts for the 10B compressor vehicle.

##### Work Planned

- Complete test cell installation, performance testing, and test cell removal of the 10B compressor vehicle.

#### 2.2.7.1 VSV Bushing Application

##### Technical Progress

Materials selected for core and ICLS engine tests are as follows:

<u>Vane Stages</u>		<u>Description</u>	<u>Material</u>
IGV-4		Thrust Washers	Composite ZX
IGV-4		Bushings	Fabroid XV
4-6		Bushings and Washers	Mechanical Carbon
Composite ZX	-	TFE-glass fabric/glass fabric/Skybond 703 polyimide adhesive.	
Fabroid XV	-	15-mil TFE-glass fabric lined metal, with polyimide adhesive.	
Mechanical Carbon	-	PBH-20 grade carbon-graphite pressed into a metal sleeve, or as a metal jacketed thrust washer.	

Thus all bushings will be metal jacketed for solidity and long life. Additional life has been provided by lengthening the journal of Stage 4 bushings from 1.0 inch to 1.25 inches (initially 0.8 inch) and was validated by endurance wear tests.

Endurance wear tests have been conducted to substantiate 18,000 hours service life. 2,500,000 rub cycles in the component wear test corresponds to 18,000 hours service life. Bushings were procured either to Stage 1 or to Stage 4 geometry, but were tested at various stage temperatures and pressures as shown in Table 2.2-II. As shown in this table, other endurance wear tests were completed during this period for exploratory purposes to identify possible backups to the primary materials.

As explained in the last semiannual report, composites of NR150 polyimide have been evaluated, since NR150 is superior to Skybond 703 and other polyimides in heat resistance. However, long term availability of NR150 is not guaranteed by Dupont.

Based on these test results, the E<sup>3</sup> VSV materials selected almost a year ago, appear to meet the E<sup>3</sup> service life of 18,000 hours, assumed equivalent to 2,500,000 test rig cycles.

#### Work Planned

Complete last remaining endurance wear test, Fabroid XV at Stage 4 conditions.

Table 2.2-II. Endurance Wear Tests - VSV Bushings.  
200,000 Cycles HDTO Plus 2,300,000 Cycles at Cruise

Test No.	Material	Vane Stg Geometry	Test Stage	Test Load (lbs)	Pressure (paig) HDTO/Cruise	Temp. (° F) HDTO/Cruise	Test Cycles (x10 <sup>6</sup> )	Total Max. Wear	
								Bushing (mils)	Washer (mils)
61	ZX (703 Resin)	1	1	62.8	$\frac{30.2}{12.4}$	$\frac{316}{190}$	$\frac{0.2}{2.3}$	6	3
62	ZX (NR150)	1	4	44.8	$\frac{75.0}{39.3}$	$\frac{623}{485}$	$\frac{0.28}{-----}$	Test Suspended: Rig Failure. 10	
63	ZX (NR150)	1	4	44.8	$\frac{75.0}{39.3}$	$\frac{623}{485}$	$\frac{0.2}{1.946}$	33	10
59	Fabroid XV	1	1	62.8	$\frac{30.2}{12.4}$	$\frac{316}{190}$	$\frac{0.2}{2.3}$	10	5
--	Fabroid XV	4	4	37.6	$\frac{75.0}{39.3}$	$\frac{623}{485}$		To be Completed	
60	Carbon PBH-20 (1.0 in.)	4	5	30.2	$\frac{75.0}{53.9}$	$\frac{723}{581}$	$\frac{0.2}{2.3}$	13	8
57	Carbon PBH-20 (1.0 in.)	4	5	32	$\frac{75.0}{53.9}$	$\frac{700}{581}$	$\frac{0.2}{2.207}$	28	13
58	GENR-150/NR150 XYLAN (0.8 in.)	4	4	34	$\frac{75.0}{39.3}$	$\frac{623}{485}$	$\frac{0.2}{1.012}$	32	31

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## 2.2.8 High Pressure Compressor Fabrication

### 2.2.8.1 Compressor Rotor

#### 2.2.8.1.1 1-6 Rig

##### Technical Progress

All hardware was received in the first and second quarters of 1979.

#### 2.2.8.1.2 1-10 Rig Build A

##### Technical Progress

All hardware was required for the 1-10 rig compressor rotor was received during the last quarter of 1979 and the first and second quarters of 1980. The last of the four powder René 95 spool preforms, to be used as backup material, has been inspected and approved for use if required.

#### 2.2.8.1.3 1-10 Rig Build B

##### Technical Progress

The second rig test rotor utilizes the same hardware previously run in the first rig test with the exception of the Stage 3 through 10 rotor blades. The Stage 3 through 7 blades were obtained from the order for the core rotor build received in the first three quarters of 1980 and the Stage 8, 9, and 10 blades (Mod A) had already been procured in 1979. All of the hardware procurement for the second rig test has been completed.

#### 2.2.8.1.4 Core

##### Technical Progress

The core compressor rotor will utilize all new hardware. The Stage 1 through 7 blades, CDP seal disk, 1-4 spool and deep retainer rings, have been received and inspected. The aft spool, Stage 5 disk and CDP seal disk have been reworked for instrumentation. The Stage 8, 9, and 10 blades are in the final manufacturing cycle and will be received early in the fourth quarter of 1981. The instrumentation lead out duct was completed and is scheduled for a bench vibration test.

#### Work Planned

- Complete instrumentation rework on the 1-4 spool.
- Receive the Stage 8, 9, and 10 Mod C blades.

#### 2.2.8.2 Compressor Stator

##### 2.2.8.2.3 1-10 Rig Stator Hardware, Build II

#### Technical Progress

Recamber of Stage 2 through 5 vanes was initiated and completed during this reporting period. Vanes damaged during the 1-10A test have either been reworked or replaced.

#### Work Planned

- Rework hardware as required during vehicle buildup.

#### 2.2.8.2.4 Core Stator Hardware

#### Technical Progress

Casting of the Stage 7 through 9 vane sectors is complete. Machining of the sectors is in progress. Casting of the OGV ring is nearing completion. Diffuser frame patterns are being assembled prior to producing the casting mold.

Recamber of Stage 2, 3, and 5 vanes is complete and Stage 4 is nearing completion. Manufacture of all other hardware components is complete with the exception of the VSV actuation hardware.

#### Work Planned

- Complete machining of Stage 7 through 9 vane sectors.
- Complete manufacture of OGV/diffuser assembly.
- Continue support of VSV actuation hardware procurement.

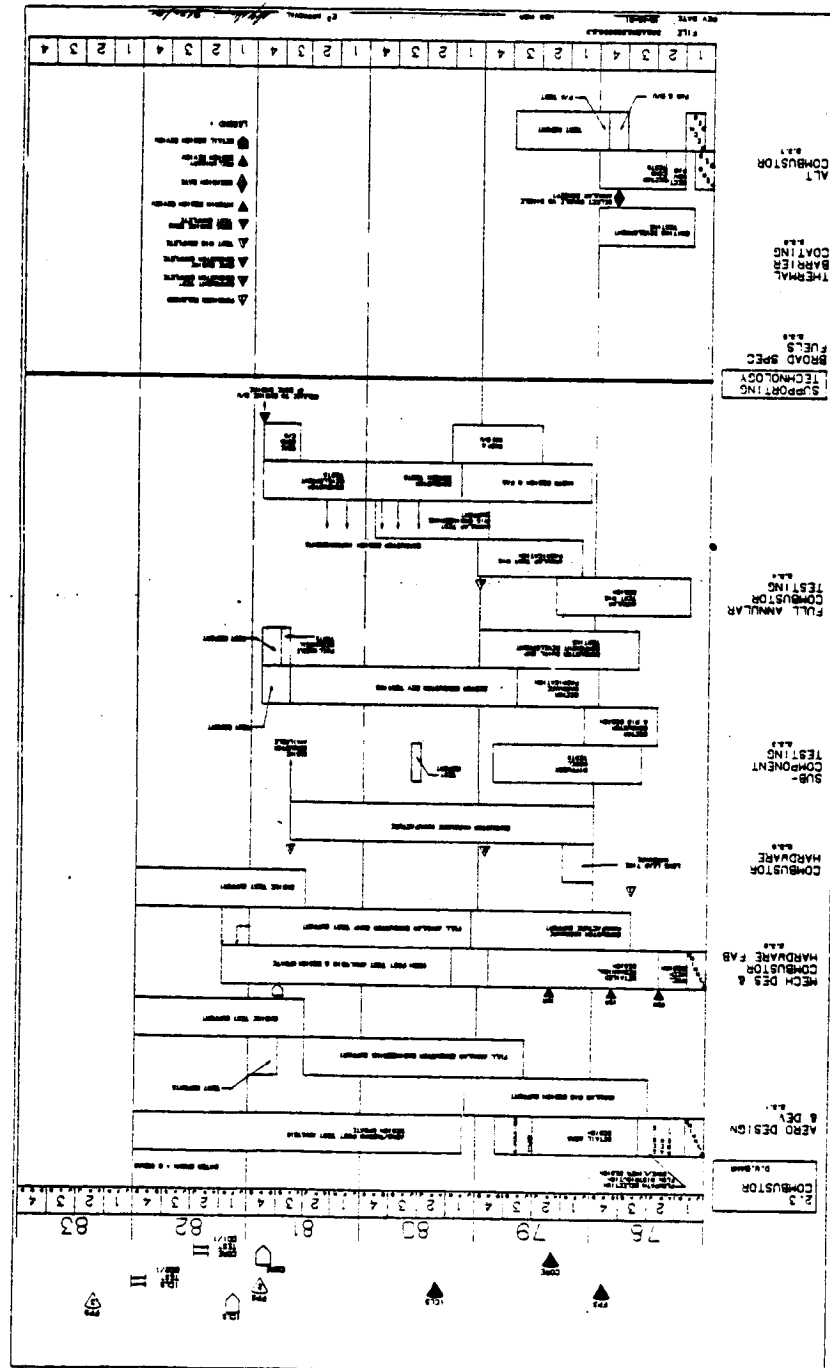
## 2.3 COMBUSTOR

### Overall Objectives

The key objective of this program is to design and develop an advanced combustion system capable of meeting both the stringent emissions and long-life goals of the E<sup>3</sup>, as well as meeting all of the usual performance requirements of combustion systems for modern turbofan engines. The specific E<sup>3</sup> emissions goals are the emissions goals standards for carbon monoxide (CO), unburned hydrocarbons (HC), oxides of nitrogen (NO<sub>x</sub>), and smoke that have been specified by the EPA for newly certified subsonic aircraft engines. These very stringent CO and HC emissions goals require very high combustion efficiencies at all engine operating conditions, including idle. The FPS combustion efficiency goal is 0.995 minimum at high power settings with a total pressure drop of 5.0% maximum.

To meet these emissions goals and other performance requirements, an advanced, short-length, double-annular combustor design concept has been selected (Figure 2.3-1). This design approach was chosen based on the low-emissions combustor design technology developed in the NASA Experimental Clean Combustor Program (ECCP) and the NASA Quiet Clean Short-Haul Experimental Engine (QCSEE) Program. A comparison of the key combustor design parameters for the NASA E<sup>3</sup>, NASA ECCP, and NASA QCSEE combustors is shown in Table 2.3-I. In these development programs, it was demonstrated that with the double-annular combustor design concept, low emissions levels could be obtained in addition to obtaining the other combustor performance capabilities required for satisfactory operation of a turbofan such as the E<sup>3</sup>. To meet the long-life goals, an advanced, double-walled, axially segmented, cooling liner design concept using both impingement and film cooling has been selected. This advanced cooling liner design concept, in conjunction with the very short length of this design, is projected to result in a combustor configuration with the requisite long-life objectives.

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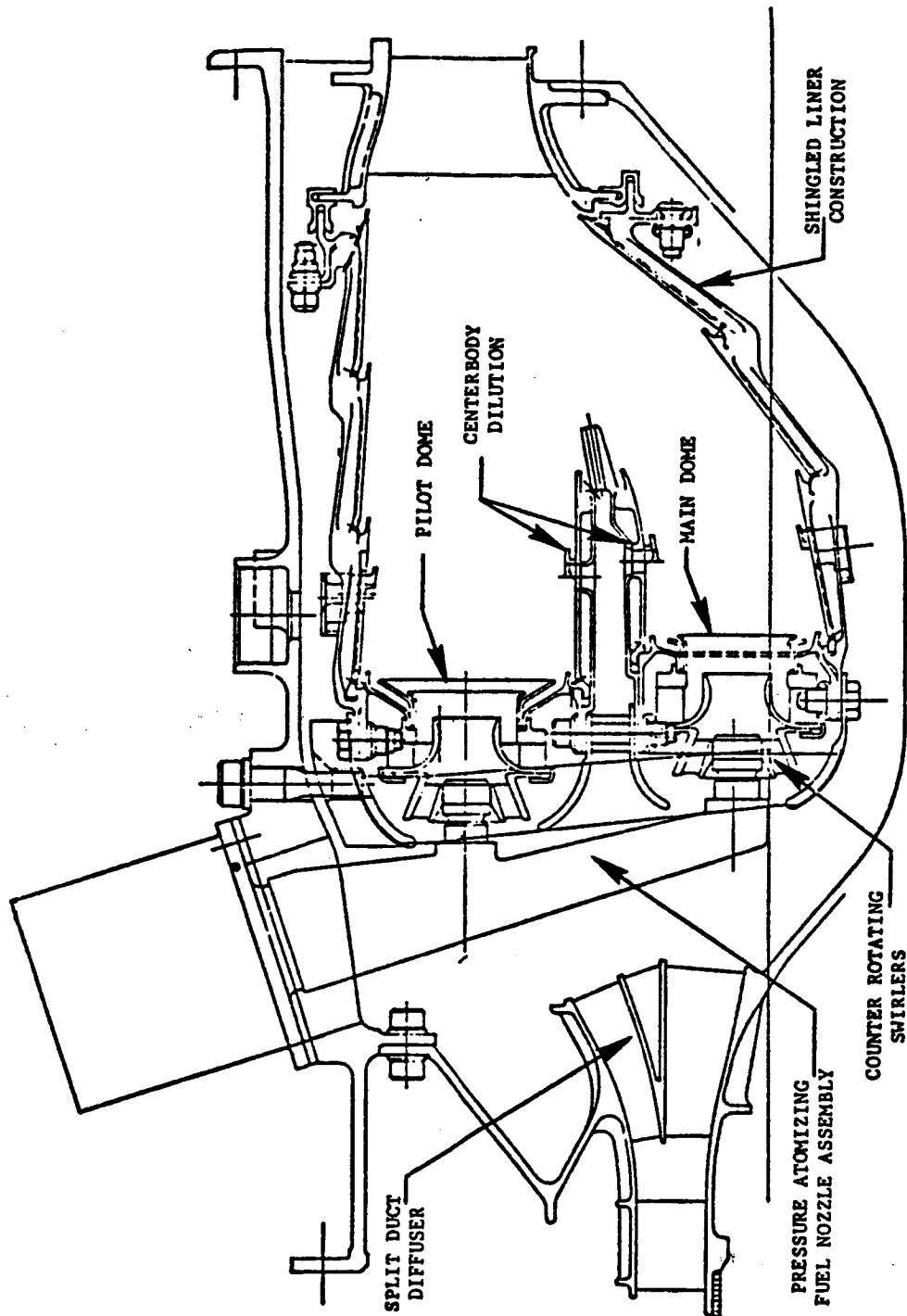


Figure 2.3-1. Combustor Design Concept.

Table 2.3-I. Combustor Aerodynamic Design Parameter Comparison.

Combustion System	E <sup>3</sup> Double Annular	ECCP Double Annular	QCSEE Double Annular
Burning Length (in.)	6.7	12.9	7.0
Pilot Dome Height (in.)	2.4	2.7	2.3
Main Dome Height (in.)	2.0	2.4	2.0
Length/Dome Height - Pilot	2.8	4.8	3.0
Length/Dome Height - Main	3.4	5.4	3.5
Number of Fuel Injectors - Pilot	30	30	20
Number of Fuel Injectors - Main	30	30	20
Reference Velocity (ft/sec)	58	75	59
Space Rate (Btu/hr-ft <sup>3</sup> -atm x 10 <sup>-6</sup> )	7.0	5.8	8.1

## Development Approach

### Basic Program (Double-Annular Combustor Design)

The overall design definition and development approach have been selected for the E<sup>3</sup> combustor. The aerodynamic and mechanical design features identified for the diffuser, cowling, dome, and liner of the combustor were based on proven design and analytical techniques evolved from other General Electric combustor designs.

Initially, an extensive series of combustion system aeromechanical design and design tradeoff studies was conducted using existing combustor design tools and correlations to define the optimum combination of the basic combustor design parameters. These design studies included the definition of the combustor inlet diffuser, combustor cooling features, the number of fuel injectors, the swirl cup design features, and the dilution airflow patterns. Based on the results of these design studies, combustion system performance predictions and emission levels were estimated. The final flowpath design was then incorporated into a mechanical design layout.

Following these initial design studies, detailed stress analysis, heat transfer analysis, and life prediction studies were made for both steady-state and transient operation at the most adverse operating conditions.

Based on these detailed aerodynamic and mechanical design studies, the detail features of the combustor evolved into engineering drawings for procurement of development test hardware.

To evaluate and confirm these design analyses efforts, subcomponent tests are being conducted. The purpose of these tests is to permit preliminary development and refinement of the emissions and performance characteristics of the combustor design prior to and during the full-annular combustor development testing. These subcomponent development tests include diffuser tests to develop the diffuser aerodynamic characteristics in order to obtain the required combustor inlet conditions at the various simulated engine conditions from idle to takeoff, individual swirl cup tests to develop the required

fuel preparation and introduction characteristics to obtain the desired combustion zone stoichiometry, and sector combustor tests to develop the pilot stage dome features to meet the idle emissions goals and develop ground-start and altitude relight capability.

The diffuser test program was conducted in a full size, full annular test rig and is complete. These tests were run with ambient temperature air-flow, and the diffuser was tested over a broad range of passage flow-split values with three different inlet velocity profiles. The results of these tests, based on measured static pressure recovery and total pressure loss coefficients for the inner and outer combustor domes, the centerbody passage, and the inner and outer combustor liner passages, indicated that the diffuser would perform satisfactorily in the development combustor test rig and in the E<sup>3</sup>. The test results have been confirmed based on measurements recorded in the development test rig.

The swirl cup spray-visualization tests were conducted to determine the effects of combustor dome pressure drop, swirl cup fuel/air ratio, and fuel/air momentum ratios on fuel spray characteristics such as spray angle, stability, and atomization. The results of these tests were utilized to select the swirl cup design features for the sector combustor and for the full-annular combustor.

The sector combustor tests are being conducted with a 60° sector of the E<sup>3</sup> combustor design. The emissions-related aspects of these tests are primarily directed toward obtaining low CO and HC emissions levels in the pilot stage at idle operating conditions and evaluating the crossfire and fuel-staging characteristics between the pilot and main stages. Tests of the baseline configuration sector combustor and several modifications to the baseline are complete. The objective of the present testing will be to select a preferred pilot stage configuration to obtain even lower idle emissions. The sector combustor tests will also continue to develop ground-start ignition capability. Several combustor configurations have been evaluated in the sector combustor test rig that have demonstrated significant improvement in low power emissions levels and ground-start ignition capability. Later in the

test program, the altitude relight capability will be investigated. Initially, these altitude relight tests will be conducted with ambient temperature air. Configurations that light within the envelope will then be tested both with cold air and with cold fuel (about  $-30^{\circ}$  F) at the air temperature and pressure corresponding to combustor conditions for the altitude and Mach number being evaluated.

A significant portion of the planned E<sup>3</sup> combustor component development effort is being performed with a full-scale annular test vehicle that duplicates the flowpath of the engine and can accommodate full-scale engine combustor hardware. Testing in the combustor test vehicle is being performed at both atmospheric and elevated-pressure conditions.

The exit annulus of the test rig is at the same radial location as the turbine nozzle of the engine. The test vehicle will simulate the cooling flows of the turbine nozzle diaphragm and first-stage turbine blades.

The OGV/diffuser section of the full-annular test vehicle simulates the aerodynamic characteristics of the airflow delivered to the combustor from the engine compressor. Provisions to add inlet airflow profiling features to simulate compressor-circumferential and radial distortion are also included. The test rig prediffuser incorporates structural features identical to those of the engine design, including flowpath simulation, strut supports, and bleed capability at the prediffuser trailing edge. Pressure-measurement instrumentation is provided along the diffuser flowpath surfaces to monitor stability and performance.

The combustor section provides the structural pressure vessel to house the combustor and duplicates the flowpath of the engine combustor housing. Ignitor port locations can be incorporated at several circumferential positions to permit selection of location flexibility based on sector combustor component test data.

Two different exit instrumentation sections are being used with this test vehicle. Atmospheric pressure tests are performed with a mechanically actuated ring mounted from the outer flange. Temperature and pressure rakes

are mounted to the ring which is traversed around the combustor circumference. With this test rig setup, combustor airflow is discharged directly to the atmosphere; the reaction zone can be viewed directly from the combustor exit. For testing at elevated pressure levels, a high pressure casing containing five internal rotating gas sample rakes is used. This exit section is capable of operation up to pressures of 300 psia.

Two different types of full-annular combustor tests are being conducted: (1) high pressure tests to develop the emissions, performance, and durability characteristics of the combustor at various simulated engine operating conditions from idle to takeoff and (2) atmospheric-pressure combustor tests to develop the required combustor exit temperature distributions and ground-start ignition capability. The altitude relight capability of promising combustor configurations will be evaluated in accompanying sector combustor tests.

The evaluation of the baseline combustor configuration as the first phase of development testing has been completed. The design information acquired in the baseline test in conjunction with preferred combustor design features evolved in the sector combustor development program were incorporated into a modified version of the baseline design.

Cold-flow calibrations of this modified E<sup>3</sup> combustor test hardware were performed to verify that the various dome and liner cooling airflows were distributed as intended. Then full-annular tests were conducted at atmospheric pressure to provide additional data on pattern factor, profile factor, and ground-start characteristics. Following completion of the atmospheric tests, evaluation of the improved design for reduced emissions was conducted at ground idle operating conditions. A final high pressure test was conducted to measure combustor metal temperatures at simulated high power conditions. Following analysis of the data from this modified configuration, additional development tests will be conducted to further improve the design.

Upon selection of the final design for engine installation, all of the design features evolved in the development program will be incorporated in the core engine combustor. This hardware will undergo a complete evaluation of all facets of combustor operation including ignition, emissions, and performance. The combustor will then be released to the core engine upon satisfactory completion of the tests.

### 2.3.1 Aerodynamic Design

The E<sup>3</sup> double-annular combustor concept is an advanced design approach which must meet the engine performance requirements as well as the emissions goals over a wide range of operating conditions. Some of the key operating conditions for the E<sup>3</sup> combustor are shown in Table 2.3-II. Operation of the engine combustor at these varied conditions requires that the combustor fuel flow be staged to the two domes as shown in Figure 2.3-2. Therefore, considerable aerodynamic development effort is anticipated to obtain satisfactory operation over this wide range of operating conditions while meeting the challenging performance and emissions goals for this engine.

At the conclusion of the last reporting period, preparations were underway to evaluate the second modification of the double-annular development combustor. These modifications were directed at improving ignition performance of the main stage dome in the ground-start subidle region. As noted in the last report, the key design changes introduced included further reductions in main stage dome airflow and modifications of the crossfire tubes to enhance main stage ignition.

The ignition performance of the Mod III configuration was very favorable, exhibiting satisfactory main stage ignition performance at core engine speeds approaching 40% PCNHR. However, the exit temperature distribution was not satisfactory. Modifications to the crossfire tubes resulted in local hot streaks on the centerbody (the same region where high local exit gas temperatures were encountered) and strong harmonic patterns were noted where the previously removed additional dome air was reintroduced in the aft panels.

In order to offset the local hot streaks at the crossfire tubes and reduce the temperature harmonics, the Mod IV configuration was evolved. This configuration eliminated the local cooling air blockage in line with the crossfire tubes. However, the general overall reduction in dome ring cooling air level was retained. The extension, added to the forward end of the crossfire tube to shelter the crossflow from the cooling air, was also removed since indications of metal heat distress were evident. Dilution air in the main stage was redistributed to provide additional mixing length. It was demonstrated in earlier tests that large quantities of Panel 2 inner dilution

was detrimental to ignition. Therefore, to enhance mixing but minimize the impact of dilution on ignition, only a small amount of Panel 2 inner dilution was introduced, and the Panel 3 inner dilution was reduced proportionately. A comparison of the Mod III and IV airflow distributions is shown in Figure 2.3-3.

After completion of these modifications, an evaluation of ignition performance was conducted on Mod IV. The results were somewhat discouraging because some deterioration in the main stage ignition performance was encountered, particularly in the core speed range of 30% to 50% PCNHR. However, the excellent pilot stage ignition demonstrated earlier was essentially unchanged. Additional design changes were incorporated in the development combustor in order to improve the main stage ignition performance, in addition to attenuating the severe hot streaks encountered. The main stage primary dilution was reduced in Mod V to further enrich the main stage dome for improved ignition. The air was reintroduced as pilot stage dilution to offset the hot streaks occurring near the outer wall on Panel 2. As a result of these modifications, some improvement in main stage ignition was noted. But exit temperature results still failed to meet the requirements.

During this period of combustor development testing, two key component tests were completed. The first 10-stage compressor development test was completed, providing data on compressor performance in the subidle region. Also, the high pressure turbine component test was completed with data being obtained in the core engine low-speed regime. The results of these component tests were encouraging because much improved compressor and turbine performance was measured in the subidle region, compared to early performance estimates used in previous start models.

The E<sup>3</sup> dynamic start model was updated with these latest component test results, and new estimates of the ground-start operating sequence were made. The key finding was that engine starting objectives could be met without compressor bleed. Also, as a result of improved compressor and turbine performance, combustor airflow increased significantly during ground start and reduced the combustor fuel/air ratios. Heat transfer analyses of the turbine components showed that turbine hardware could withstand the combustor exit temperatures associated with these lower fuel/air ratios. Based on these findings, it was

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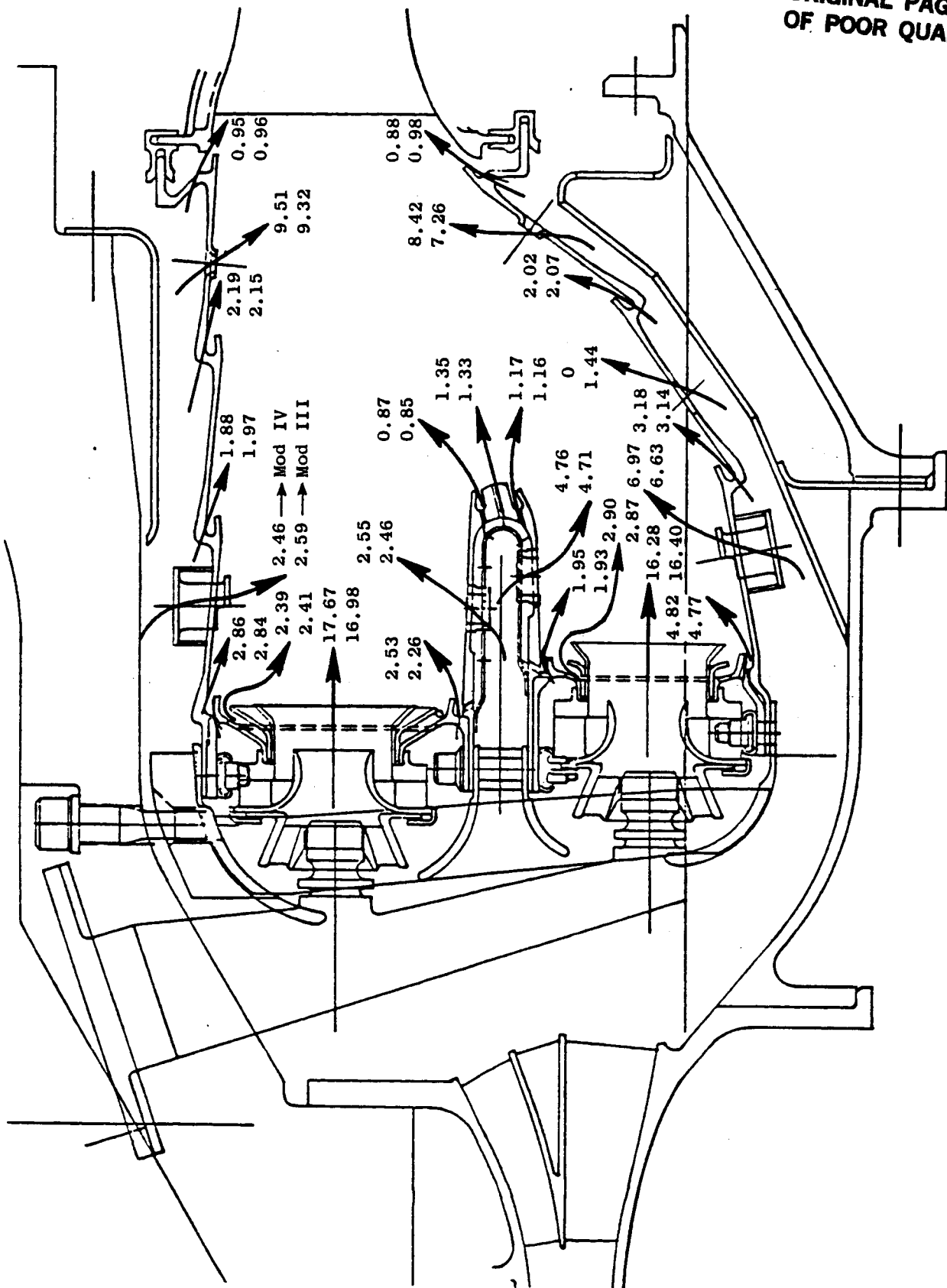


Figure 2.3-3. Comparison of Mod III and Mod IV Airflow Distributions.

concluded that the ground start sequence could be executed with only the pilot stage fueled, as originally intended. The combustor fuel/air ratios expected during the start sequence for the new model are shown in Figure 2.3-4 and compared to the previous values over the start region of interest. As a result of these lower fuel/air ratios, the expected peak temperatures are significantly reduced as shown in Figure 2.3-5.

Therefore, the combustor aerodynamic design was redirected back to the original concept of a rich pilot stage dome and a lean main stage dome. The original concept had the desirable feature of a simplified starting sequence (where only the pilot stage is fired through ground idle) and offers the greatest potential for meeting all of the emissions objectives.

Subsequent to the decision to revert back to the original design concept, the full-annular development combustor was again modified (Mod VI) to incorporate the desired design features. The key design changes incorporated included:

- Installed high-flow swirlers to the main stage dome to restore high dome velocity and low residence time.
- Returned dome cooling holes to uniform patterns, thereby eliminating local blockages in the area crossfire tubes.
- Closed the dilution holes added to Panel 2 of the outer liner.

These modifications accomplished the following changes: (1) conversion of the development combustor back to the original lean main stage dome concept, (2) trimming of the inner passage average temperature profile, and (3) enriching the pilot stage dome to improve low-power emissions and ground start ignition.

The high-flow swirlers introduced in the main stage increased the swirl cup flow level from 16.4%  $W_c$  to 23.0%  $W_c$ . The inner liner Panel 2 dilution added for earlier tests was retained to introduce about 2%  $W_c$  for profile trim. The pilot dome swirl cup was retained, causing the airflow to remain unchanged. However, the flow level was about 1.5%  $W_c$  lower than the earlier Mod I design (Figure 2.3-6).

The ground-start ignition performance of Mod VI was evaluated based on the new ground-start cycle which incorporated the revised input based on

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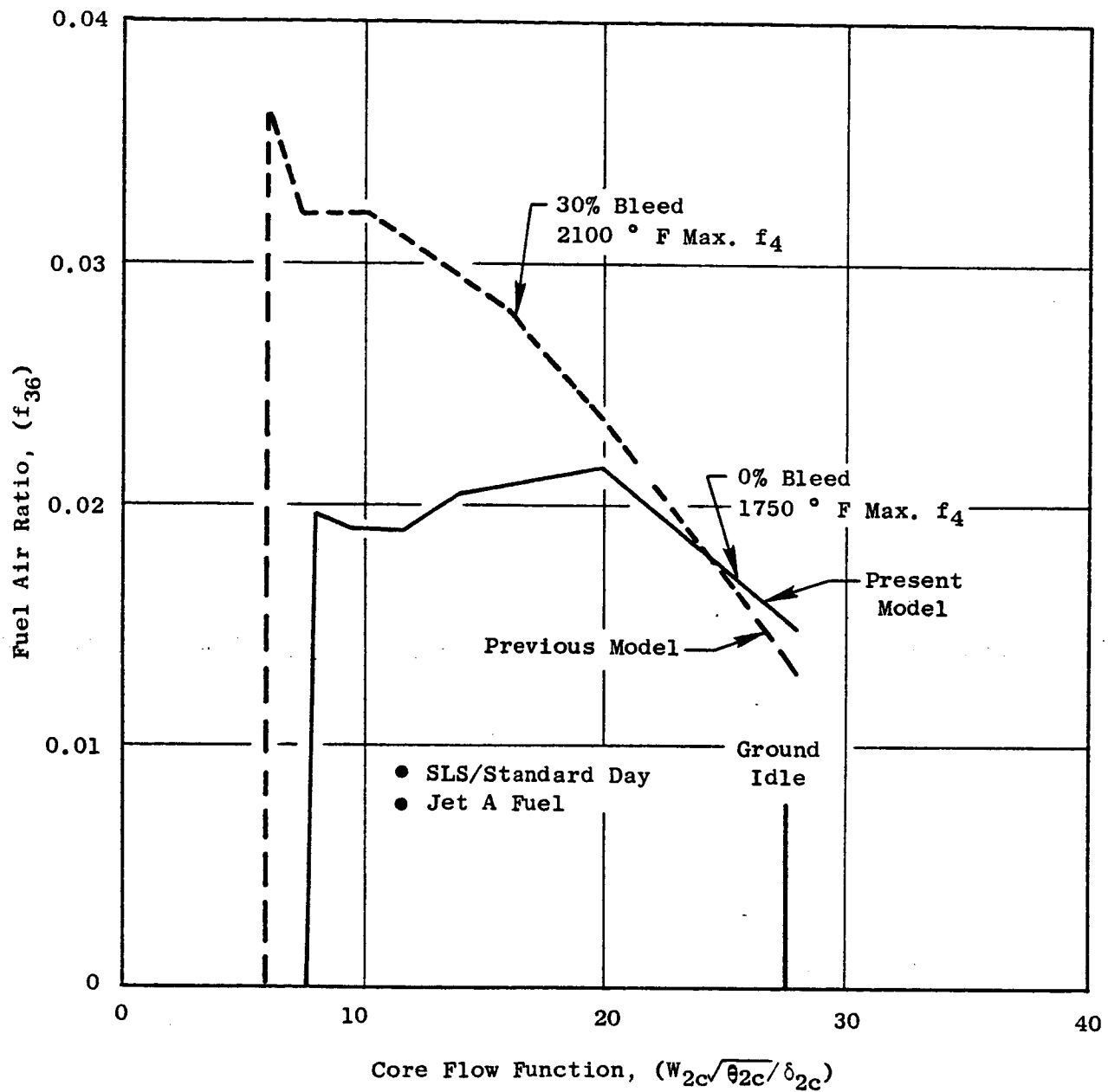


Figure 2.3-4. Comparison of Core Engine Start Models.

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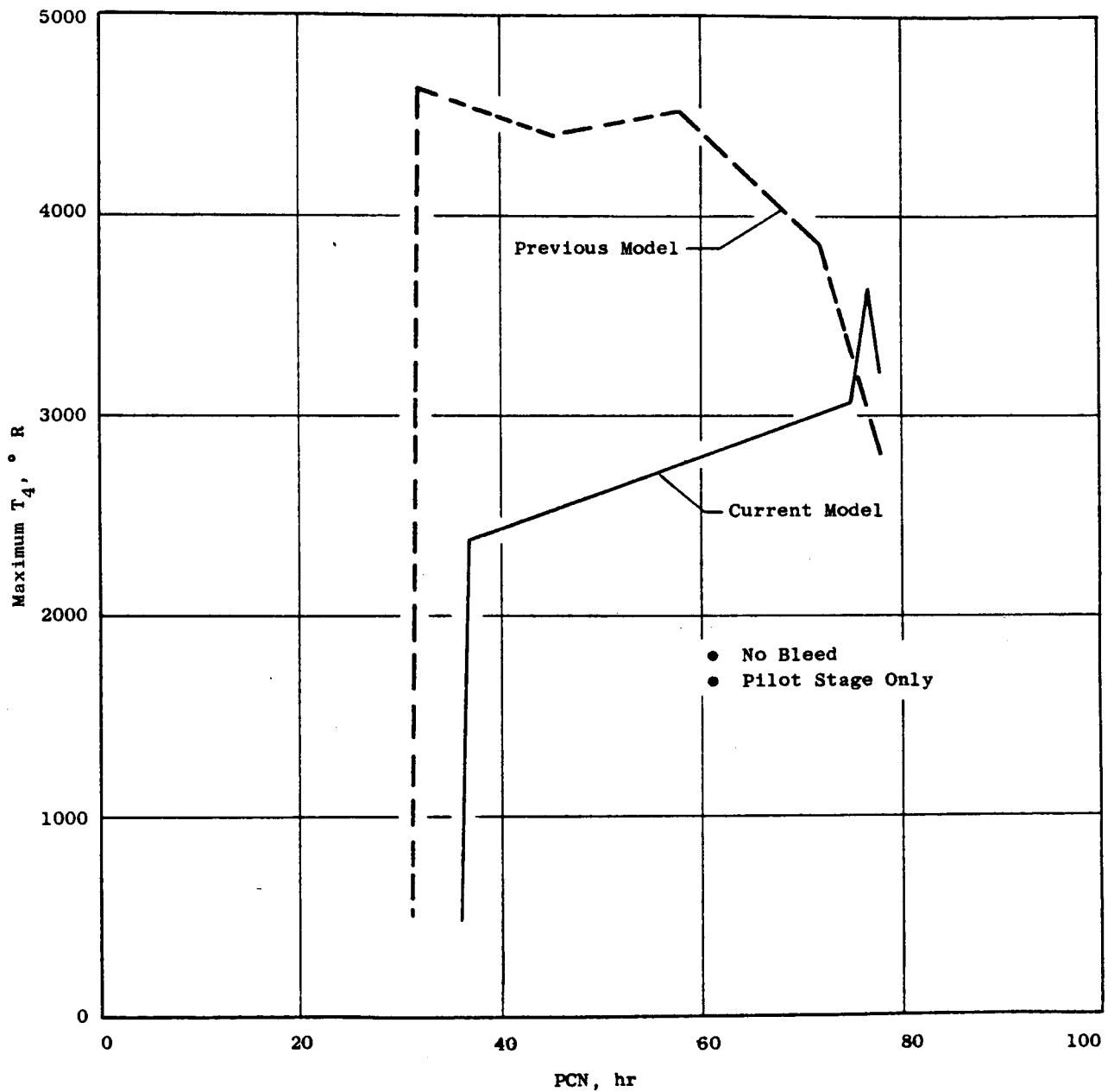


Figure 2.3-5. Maximum Local Turbine Inlet Temperature.

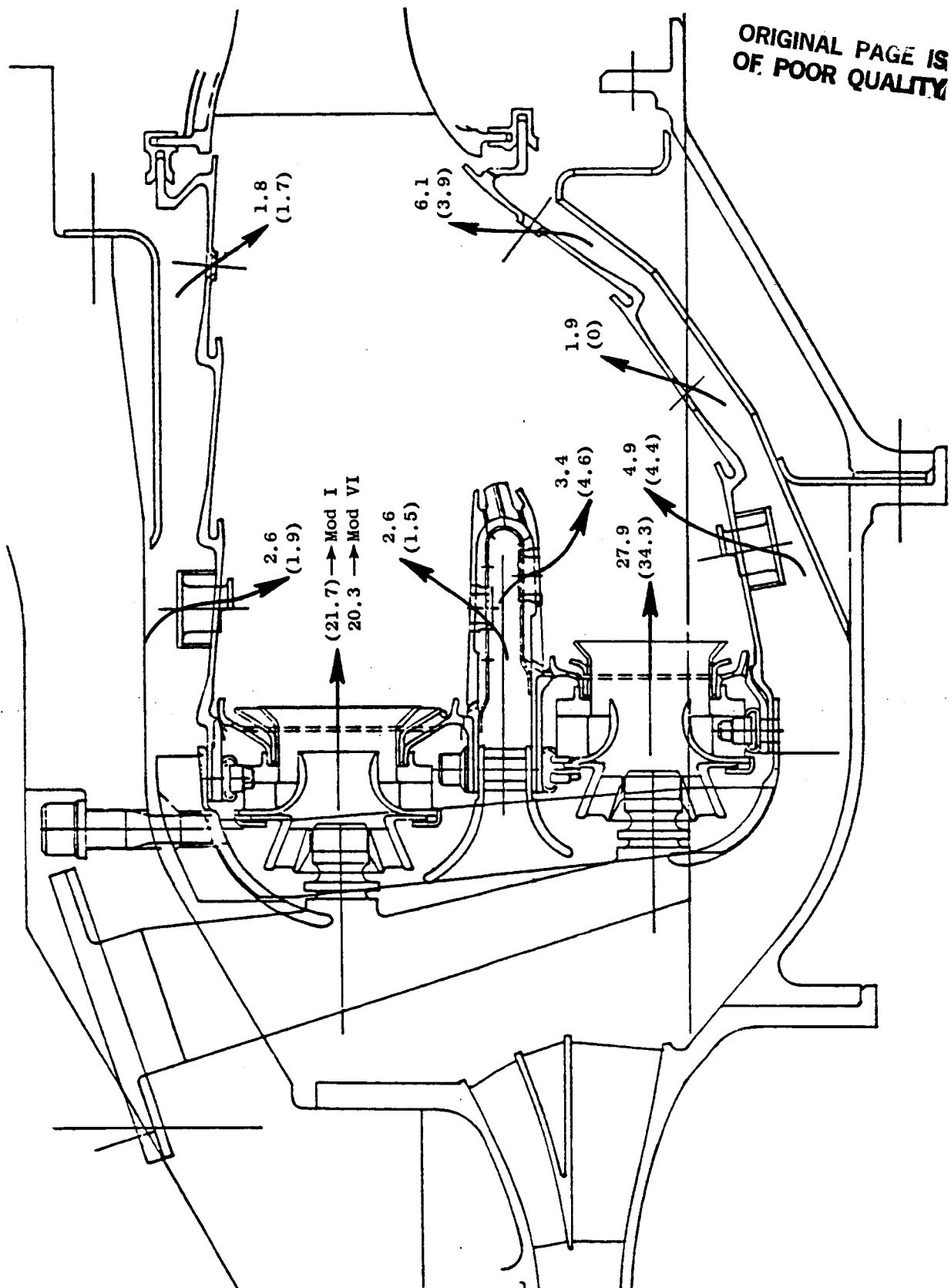


Figure 2.3-6. E<sup>3</sup> Development Combustor Mod VI Airflow Distribution, Percent W<sub>C</sub>.

recent core component test results. The results were very encouraging. Satisfactory pilot stage ignition was obtained for all conditions tested at atmospheric pressure with and without bleed simulation. Even further improvements would be expected at true cycle combustor inlet pressure.

As in the previous ignition investigations with the high airflow main dome, very high fuel/air ratios were required to obtain full propagation of the main stage. At ground idle and above, a main dome fuel/air ratio of about 0.022 was required. This is about twice the level required for full propagation in the pilot stage. However, significant improvements in ignition are expected at the true cycle conditions.

Next, an atmospheric performance test was conducted on the modified full-annular development combustor. The results for this configuration were expected to be very similar to those obtained with the Mod I configuration, except for a reduction in the exit profile temperature levels at the inner immersion. This reduced inner immersion temperature was anticipated because of the introduction of dilution air in the Panel 2 inner liner. The results were somewhat disappointing. There was some minor reduction in the inner immersion temperature, as expected, but the pattern factor was unsatisfactory with the peak temperatures exceeding the goal levels by a considerable amount. A detailed inspection of the hardware following the test revealed some significant hardware quality problems. Most noticeable were dilution hole alignments in the liners and out-of-roundness of the emissions reduction sleeves located in the dome. These poor quality features are suspected to be the result of extensive rework and modifications incurred over the last 24 months and were the source of the poor pattern factor results obtained with this configuration. Therefore, the combustor was disassembled and the discrepant items repaired prior to repeating the test.

Major refurbishment was centered on areas of the primary combustion zone of both domes. The emissions reduction sleeves were replaced in both pilot and main stage domes. The dilution thimbles were removed and realigned to be perpendicular to the liner walls. The centerbody dilution holes were deemed acceptable and were not removed but were polished to remove any burrs which might have existed. In addition, a small quantity of airflow was added to the Panel 2 inner liner to further improve the profile.

This development combustor configuration, designated Mod VII, was evaluated for exit gas temperature performance characteristics at atmospheric pressure. The results were encouraging. At the design operating condition, a pattern factor of 0.275 was demonstrated. This represents a significant improvement over the Mod VI results and closely approaches the program design goal of 0.250. Inner immersion temperatures still slightly exceed the design limit. Based on the performance improvement obtained with the Mod VII configuration, the development combustor was next evaluated at true pressure conditions for ground-start ignition performance and low-power emissions.

The tests were conducted by setting steady-state conditions for each test point defined and determining the required fuel flow to light the pilot stage. Successful ignition was noted by thermocouples located just downstream of the swirl cups (through the dilution holes) in the pilot stage dome. The spark plug was located in line with the center at the dilution station axial plane. The spark plug which provides two sparks/second and delivers about two joules energy/spark is energized, and Jet A fuel is introduced until ignition and propagation are indicated by the thermocouples. Once ignition is obtained, fuel flow is increased further until full propagation is obtained.

Testing is underway at the ambient inlet temperature conditions defined in Table 2.3-VI. The data obtained thus far is presently being analyzed in order to determine the altitude relight performance of the Mod VI sector combustor.

#### Work Planned

Altitude relight performance tests will be completed which will complete the Subcomponent Testing Program and the WBS 2.3.3 Task. A summary report will be compiled to document and present the overall results of the subcomponent Test Program.

#### 2.3.2 Component Fabrication and Test Support

The core engine combustor manufacture is essentially complete. All major components were released for final manufacture in May 1981 when the core

engine combustor aerodynamic configuration was finalized. These parts, which include the domes, centerbody, and liners, have been received and are currently undergoing flow check and instrumentation prior to initial component testing.

Several engine combustor hardware modifications were necessary in order to obtain the proper combustor airflow distribution. Cooling hole sizes in the domes, centerbody, and liners were increased to accommodate a ground-start sequence involving both fueled pilot and main stage domes. When the E<sup>3</sup> dynamic start model was revised to incorporate the latest results from the turbine and compressor component tests, the results showed that the ground-start sequence could be executed with only the pilot stage fueled, as originally intended. The combustor design was then reverted back to the original design concept. These changes in combustor airflow distribution were incorporated into the hardware, and the release for final manufacture was issued in May 1981.

A photograph of the outer support liner is shown in Figure 2.3-7. All impingement cooling and dilution holes were incorporated by laser hole drilling. This new technology allows much more efficient manufacture, plus significant savings in cost and manufacturing time. A closeup view of the liner showing the laser-drilled holes is shown in Figure 2.3-8.

The engine centerbody features a thermal barrier coating, tip slots to reduce operating stresses, and a shortened tip to achieve adequate structural rigidity. An overall view of the centerbody and a closeup view of the centerbody tip are provided in Figures 2.3-9 and 2.3-10, respectively. A listing of all engine combustor hardware is provided in Table 2.3-III.

The only outstanding engine hardware deliveries are the ignitor cables and fuel nozzles. The ignition cables will be delivered well in advance of engine test schedule needs. The fuel nozzle manufacturing cycle has experienced significant slippage due to unanticipated manufacturing problems. However, these problems have been resolved, and delivery of the core engine fuel nozzles is scheduled for early October of this year. An initial engine fuel

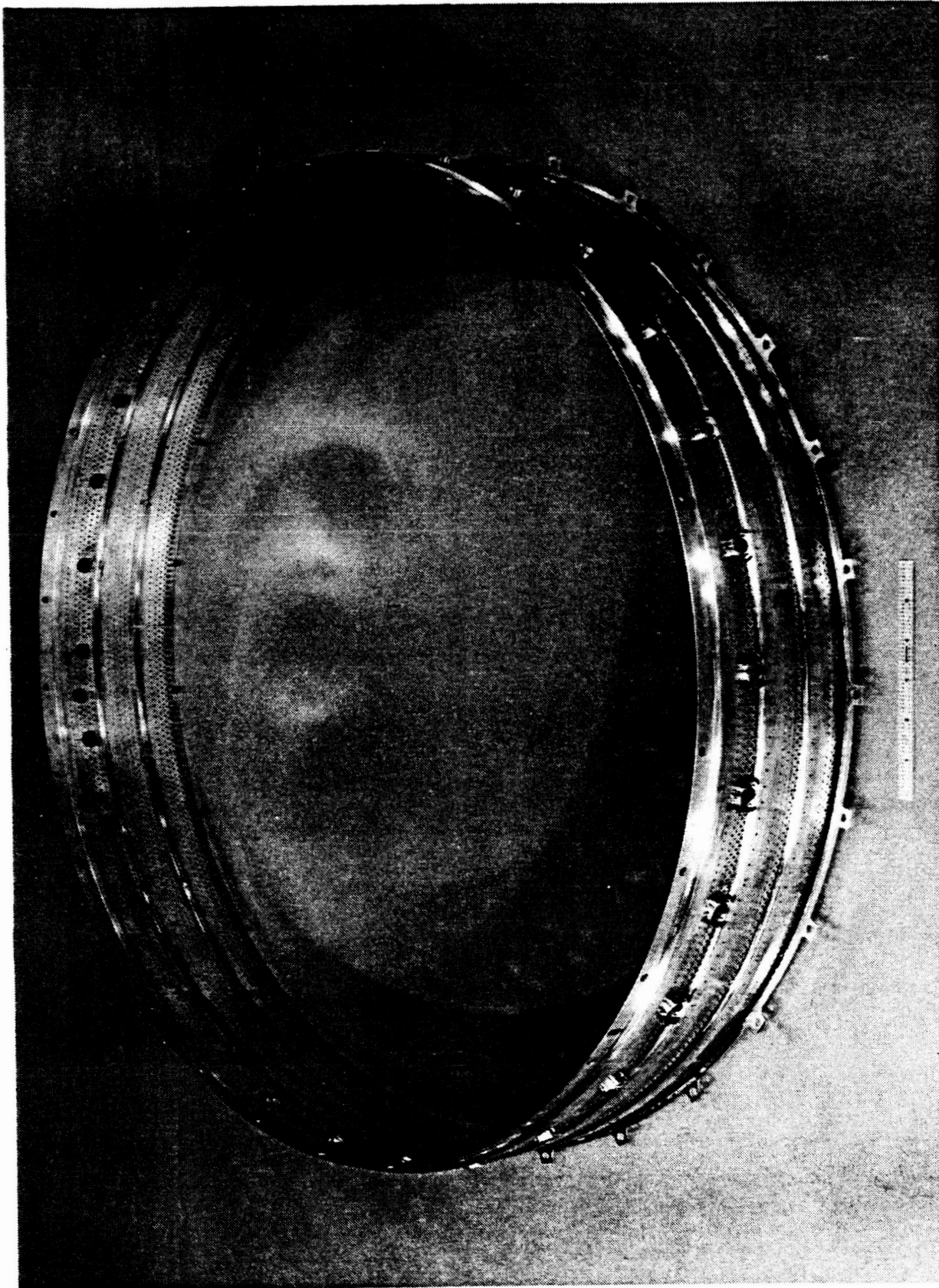


Figure 2.3-7. E3 Engine Combustor Outer Support Liner.

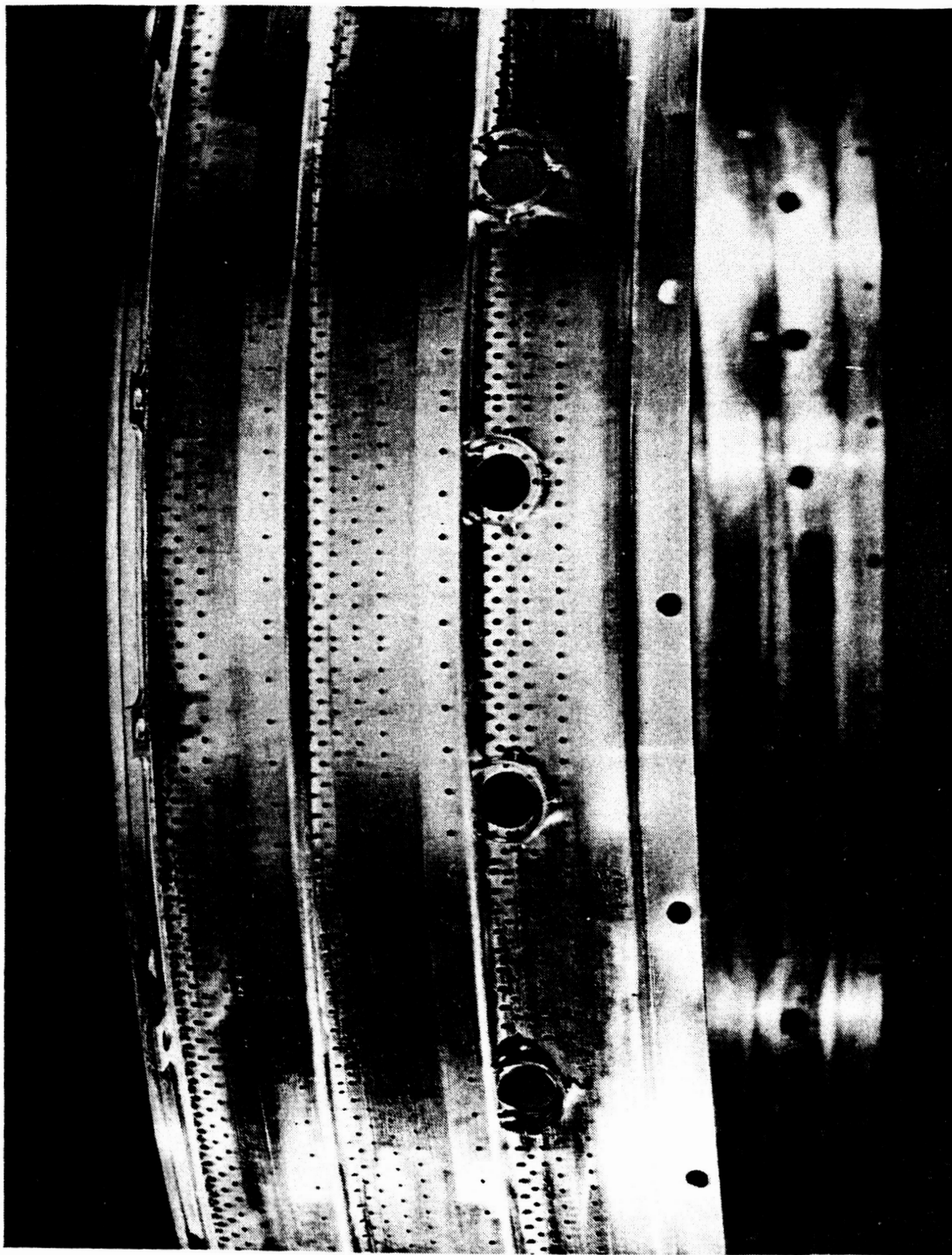


Figure 2.3-8. Laser Drilled Holes in E<sup>3</sup> Combustor Outer Support Liner.

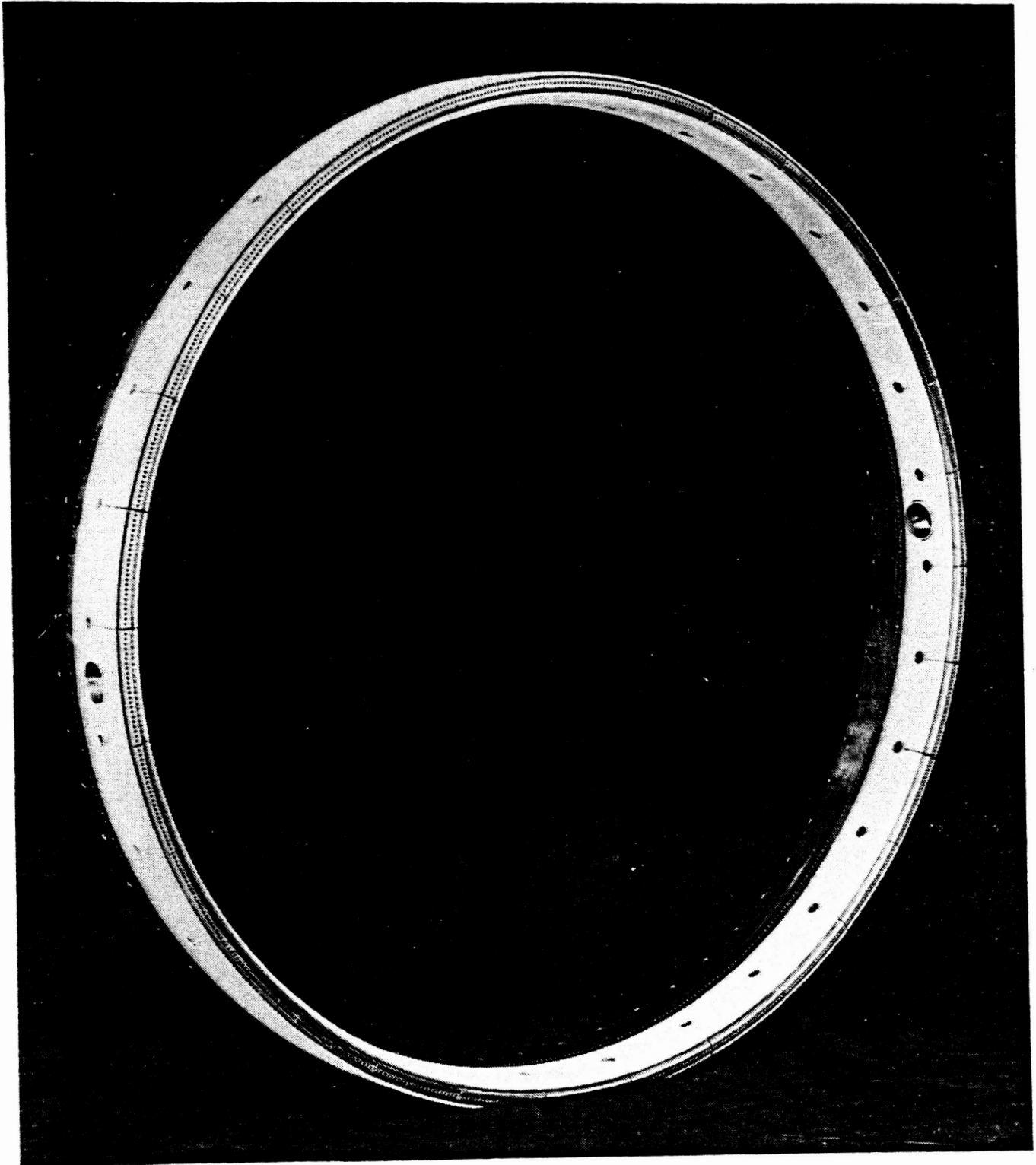


Figure 2.3-9. E<sup>3</sup> Engine Combustor Centerbody.

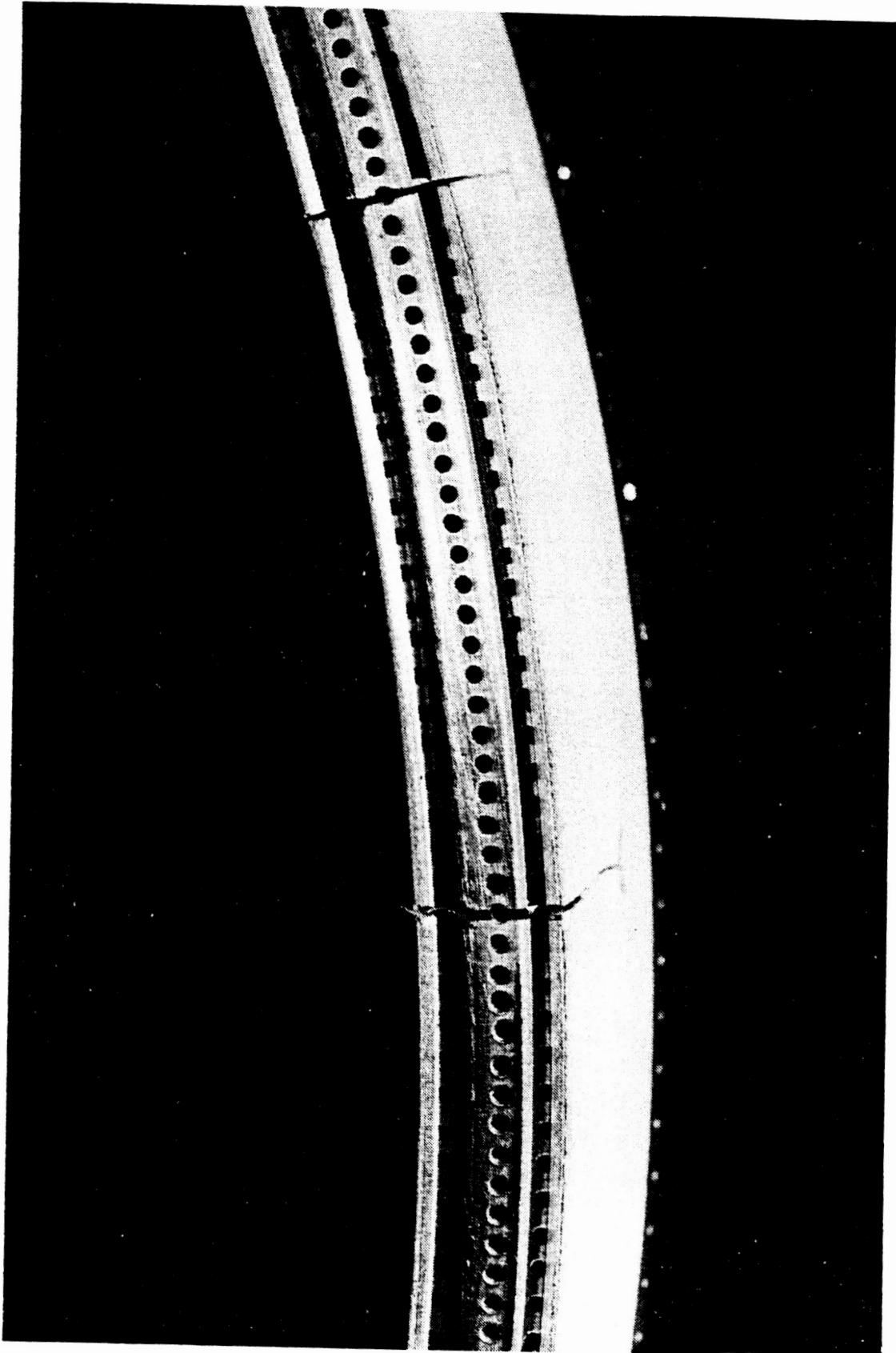


Figure 2.3-10. View of E<sup>3</sup> Engine Combustor Centerbody Tip.

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Table 2.3-III. Available Engine Combustor Hardware.

Item	Part Number	Quantity
Outer Impingement Liner Forging	4013267-459P02	3
Inner Impingement Liner Forging	4013267-460P02	3
Combustor Support Pins	4013249-922P01	65
Outer Aft Seal	4013249-931P01	2
Inner Aft Seal	4013249-932P01	2
Centerbody Forging	4013267-586P01	2
Shingle Castings	4013249-913/914/915/911	325
Outer Liner Retainer	4013249-446P01	2
Inner Liner Retainer	4013249-447P01	2
Combustor Casing Forging	4013267-466P01	2
Inner Fuel Manifold	4013279-056G01/G02	2 each
Outer Fuel Manifold	4013279-055G01/G02	2 each
Primary Fuel Manifold	4013279-055G01/G02	2 each
Primary Swirler Casting	4013267-587P01	205
Secondary Swirler Casting	4013249-442P01	205
Primary Swirler Housing Casting	4013267-585P01	205
Dilution Eyelet Casting	4013249-933P01/P02	200 each
Fuel Nozzle Seals	4013279-001P01	125
Fuel Manifold Bracket	4013279-095G01	20
Ignitor Dilution Eyelet	4013249-452P01	4
Shingle Retainer Rings	4013249-450P01/P02/P03	12
Instrumentation Seal	4013279-002P01	65
CDP Bleed Cover Plate	4013279-012P01	8
CDP Bleed Seal Plates	4013279-011P01	20
Ignitor Seal	4013204-109P01	10
Outer Support Liner	4013249-929P01	2
Inner Support Liner	4013249-930P01	2
Fuel Nozzle Forging	4013279-042P01	95
Ignitors	4013204-112P02	12
Ignition Exciter Box	910M52-P110	2
Miscellaneous Fasteners		4.5 Combustors
Outer Case Machining	4013297-050P01	1
Liner Shingle Machining	4013249-919/920/921/917	110
Outer Dome Assembly	4013267-595G01	1
Inner Dome Assembly	4013267-596G01	1
Outer Support Liner Hole Drilling	4013249-568G01	1
Inner Support Liner Hole Drilling	4013249-567G01	1
Centerbody	4013267-589G01	1
Liner Dilution Eyelets	4013249-933P01/P02	60
Cowl Assembly	4013297-594G03	1

nozzle has been received and flow checked. Overall hardware quality is excellent. A photograph of the fuel nozzle is shown in Figure 2.3-11. Flow calibration of the sample fuel nozzle indicates the hydraulic characteristics will meet the engine design requirements.

#### Work Planned

- Follow final hardware manufacture and prepare combustor components for engine testing.
- Provide mechanical design support for both engine combustor component and core engine test programs.

#### 2.3.3 Subcomponent Tests

Sector test activity was directed primarily at supporting development activities of the full annular test to improve main stage ignition. Additional testing was conducted in order to evaluate the low-power emissions performance of the final sector combustor configuration. The final test phase of the sector combustor was related to evaluation of the pilot stage ignition at simulated altitude and Mach numbers within the E<sup>3</sup> operating envelope.

Prior to embarking on the main stage ignition improvement effort, an evaluation of the low-power emissions performance of the Mod VI sector combustor configuration was conducted. The purpose of this test was to assess how closely the selected pilot stage flow distribution would meet the emissions goals for CO and HC. The results are shown in Figure 2.3-12 for CO and HC at the 6% ground idle condition. CO emissions levels meet the target level, and the HC emissions closely approach the target level. Emissions were also evaluated at simulated approach conditions for the pilot-dome-only fueled. Emissions levels, when adjusted to true cycle conditions, were 1.79, 0.02, and 12.1 for CO, HC, and NO<sub>x</sub>, respectively. These levels are consistent with earlier measurements for the approach condition with the pilot-dome-only fueled. Based on these test results, the full-annular combustor will be modified as appropriate in order to obtain the low-emissions characteristics demonstrated in the Mod VI design.

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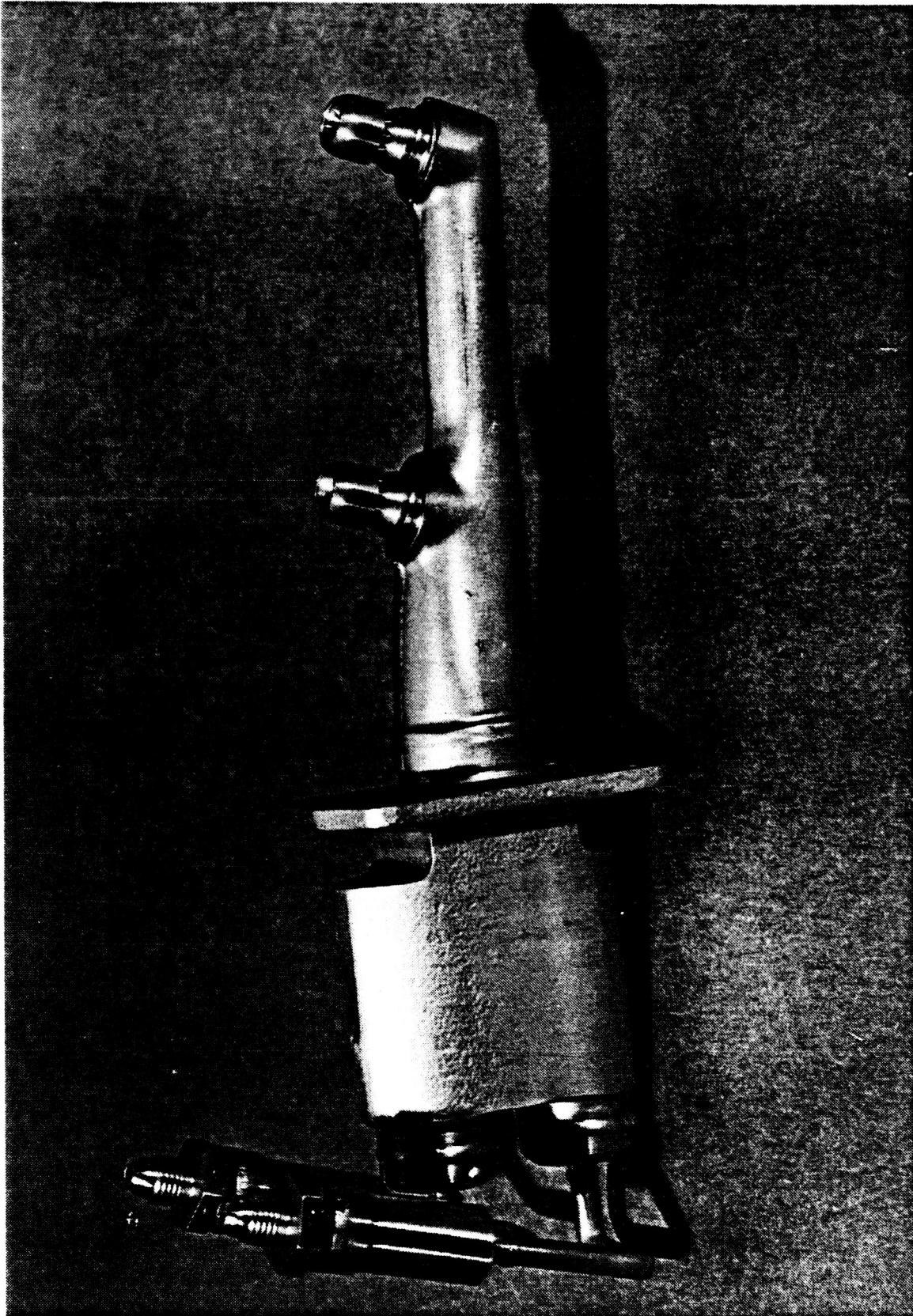


Figure 2.3-11. E<sup>3</sup> Engine Combustor Fuel Nozzle.

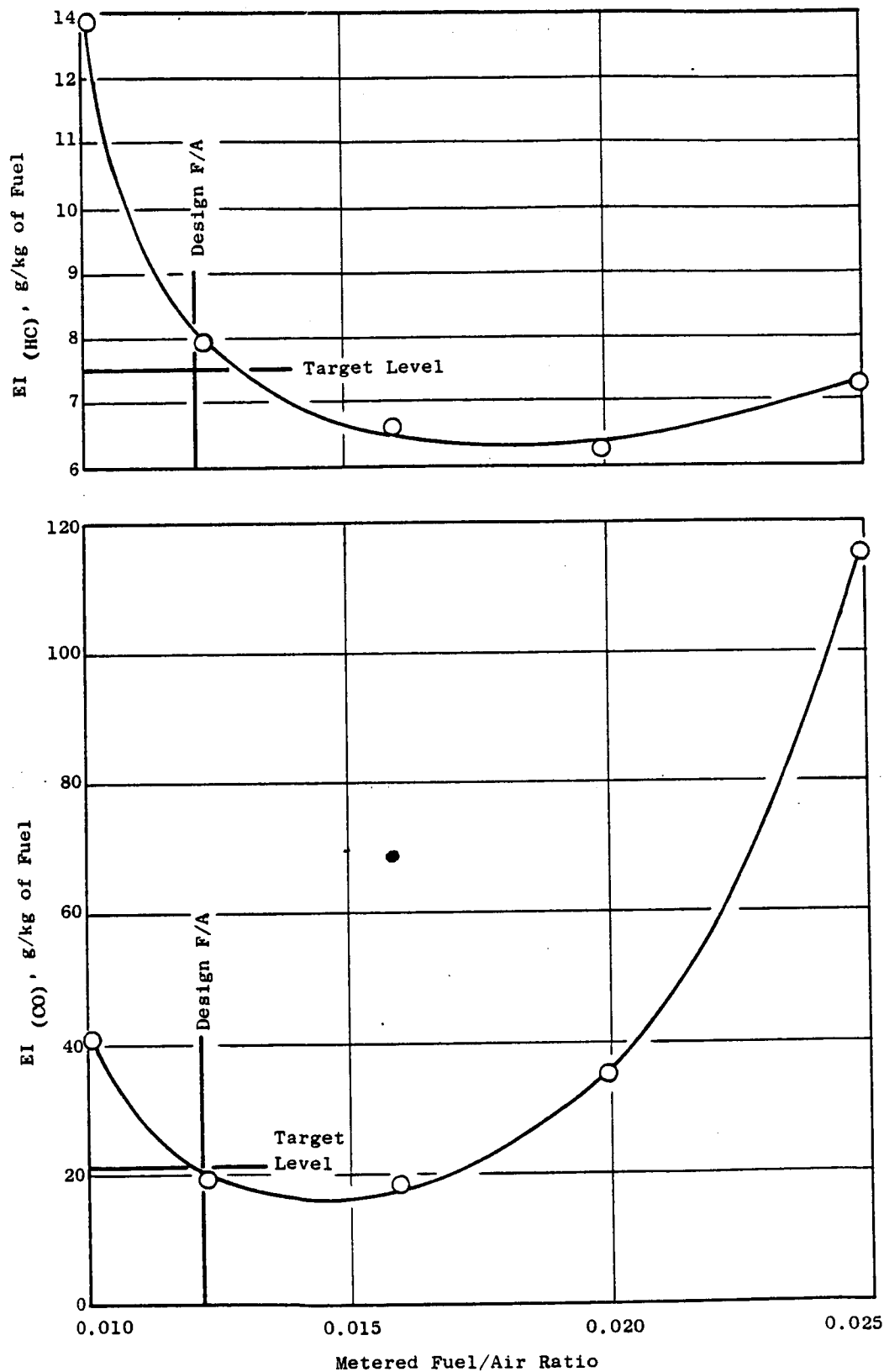


Figure 2.3-12. E<sup>3</sup> Sector Combustor Emissions Test, Mod VI Configuration;  
EI<sub>(CO)</sub> and EI<sub>(HC)</sub> Versus F/A at 6% Ground Idle.

A series of fixes was investigated on the Mod VI combustor configuration, a rich main stage dome version of the full-annular configuration, in order to improve main stage ignition performance. The various design features evaluated are shown in Table 2.3-IV. A comparison of Mod V and VI combustor airflow distributions is shown in Figure 2.3-13. The modifications tested are depicted in Figure 2.3-14.

Mod VI configuration features were originally intended to improve the idle emissions levels. The modifications included a reduced pilot stage secondary airflow, increased pilot stage dilution airflow, and reduced pilot stage Panel 1 cooling airflow relative to the Mod V configuration. The ignition test results for the Mod VI configuration were very similar to those of the Mod V configuration and were used as the reference to which the four subsequent configuration results were compared.

In Mod VI-A, every other passage in the main stage primary swirler was blocked in addition to reducing main stage splash plate cooling by approximately 30%. This was intended to enrich the main stage dome, thereby enhancing crossfire. It was observed during the test that main stage ignition occurred in the vicinity of the dilution jet plane rather than in the richer dome region. This indicated the possibility that the ignition source, (that is, the crossfire tube) is located too far downstream. This same phenomenon was observed later during the full-annular ignition test.

For the Mod VI-B configuration, the blockage from the pilot stage secondary swirler was removed to allow a stronger swirl cup recirculation zone and possibly force more flame through the crossfire tube into the main stage. But the test results for this configuration indicated no improvement in main stage ignition performance over the previous configuration, and the same phenomenon of main stage ignition occurring near the primary dilution jet persisted.

An extension was added to the main stage side of the crossfire tube for the Mod VI-C configuration. The purpose of the extension is to shelter the flame passing through the tube from being swept downstream by cooling air. Results of the ignition test on this configuration showed only a modest improvement in crossfire and ignition performance. Another extension was added, this time to the pilot stage side of the crossfire tube for the Mod

Table 2.3-IV. Mod VI Combustor Configuration Changes.

Configuration	Features
Mod VI	<ul style="list-style-type: none"> <li>● Reduced pilot stage secondary swirler area by blocking 1/3 of vane passages.</li> <li>● Increased pilot stage primary dilution.</li> <li>● Reduced pilot stage ring cooling.</li> </ul>
Mod VIA	<ul style="list-style-type: none"> <li>● Reduced main stage primary swirler area.</li> <li>● Reduced main stage splash plate cooling.</li> </ul>
Mod VIB	<ul style="list-style-type: none"> <li>● Modified pilot stage secondary swirler to original Mod VI design.</li> </ul>
Mod VIC	<ul style="list-style-type: none"> <li>● Added extension to main stage side of crossfire tube.</li> </ul>
Mod VID	<ul style="list-style-type: none"> <li>● Added extension to pilot stage side of crossfire tube.</li> </ul>

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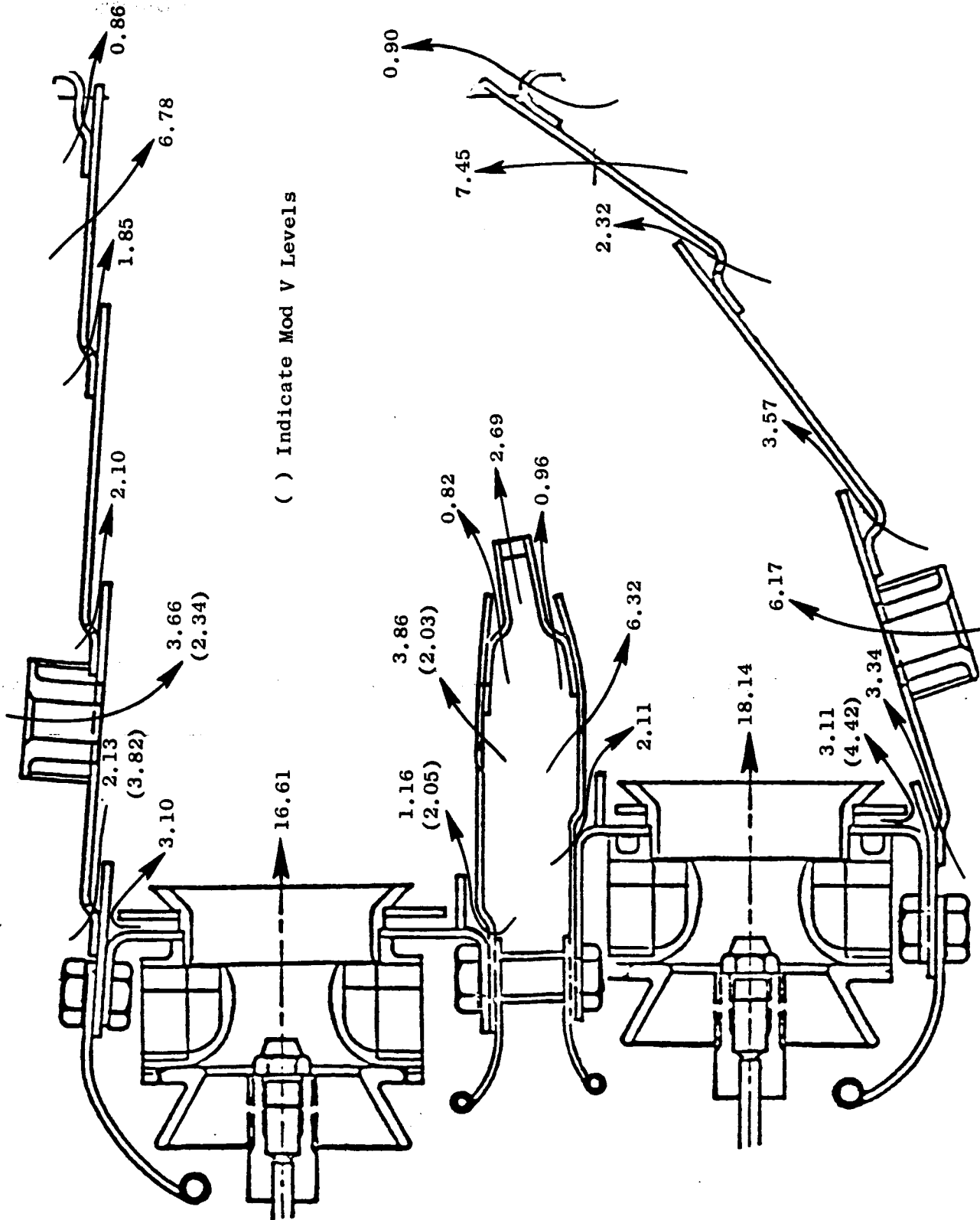


Figure 2.3-13. E<sup>3</sup> Sector Combustor Airflow Distribution Mod VI and Mod V Comparison.

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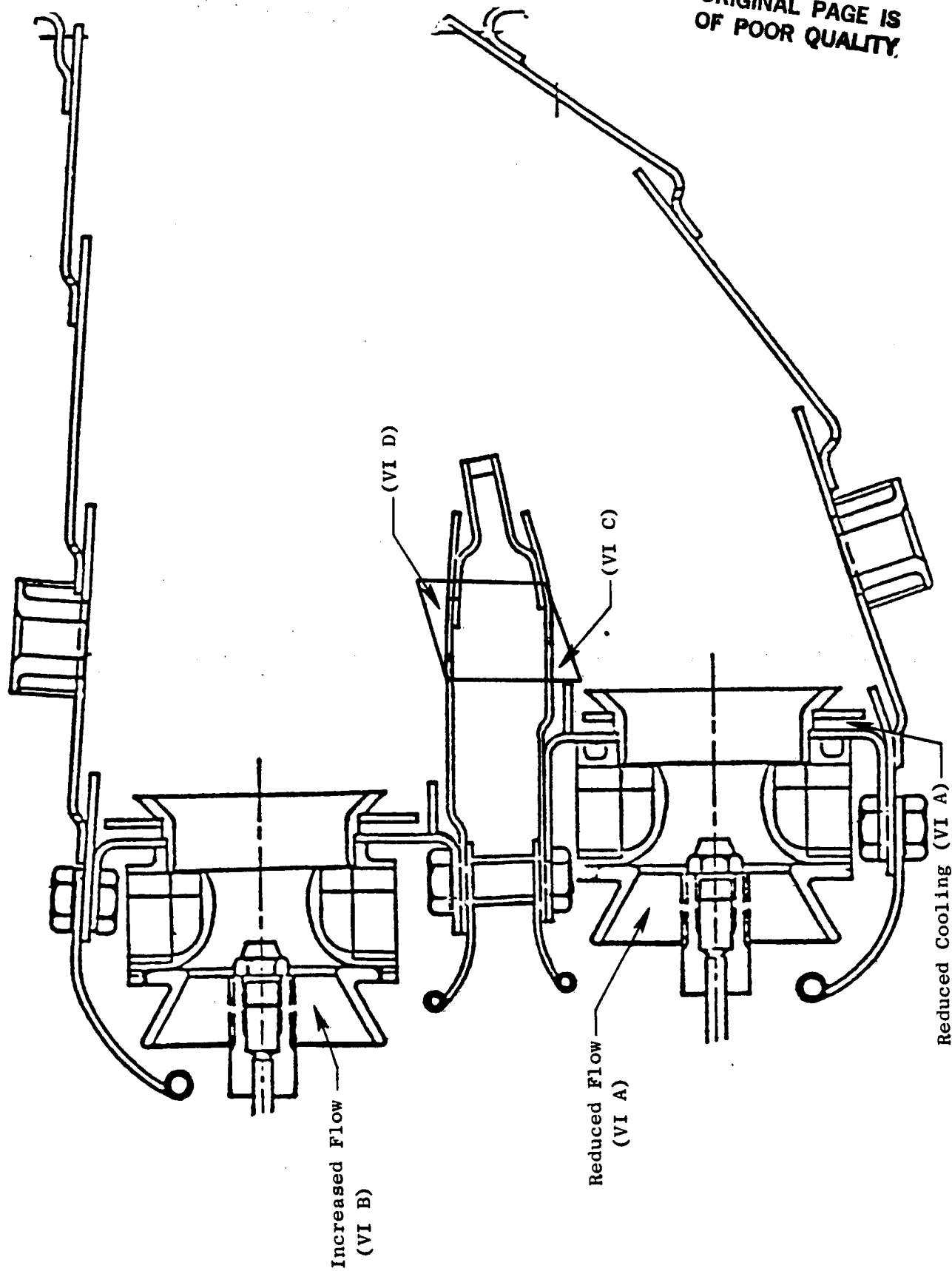


Figure 2.3-14. Sector Combustor Modifications.

VI-D configuration. The purpose of this extension is to capture the flame from the pilot stage and direct it into the crossfire tube. Test results after this modification showed a significant crossfire performance improvement at the lower core speeds. At the higher core speeds, the crossfire fuel/air ratios remained approximately the same as those obtained for the preceding configuration.

As shown in Figure 2.3-15, only the Mod VI-D configuration with an extension in the pilot stage side of the crossfire tube appears to result in a significant improvement in the main stage crossfire performance. One concern for this design feature is that special attention would have to be directed toward cooling the extension since it projects into the pilot stage gas stream. Before pursuing the extension approach further, one additional design change to the crossfire tube was investigated. The original cylindrical crossfire tube was redesigned into a semicircle with a large diameter such that it had an equivalent area to the cylindrical design. The intent of the modification was to move the flow area of the crossfire tube as far forward on the centerbody as possible. Previous ignition tests had indicated that such a change might help propagate the flame from the pilot stage to the main stage.

The results of this configuration compared to the results of the last test with the original crossfire tube are shown in Figure 2.3-16. The passage of the flame from the pilot to the main stage was more definite with the modified crossfire tube configuration than in any of the previous tests, especially at the lower core speeds, which may explain the somewhat improved crossfire performance at the 21% and 32% core speeds. With this design, the ignition performance of the main stage is equivalent to that obtained with the crossfire tube extension. Therefore, it is a more desirable approach since additional cooling would not be required. During this time period, the ground-start studies resumed and, as a result, ground starts on pilot stage only were established for the engine. Therefore, efforts to improve main stage ground-start ignition were abandoned, and evaluation of the pilot stage ignition with the new ground-start cycle was initiated.

An ignition test was conducted on the Mod VI configuration using the revised E<sup>3</sup> sls/standard day start cycle. The test point schedule for the new

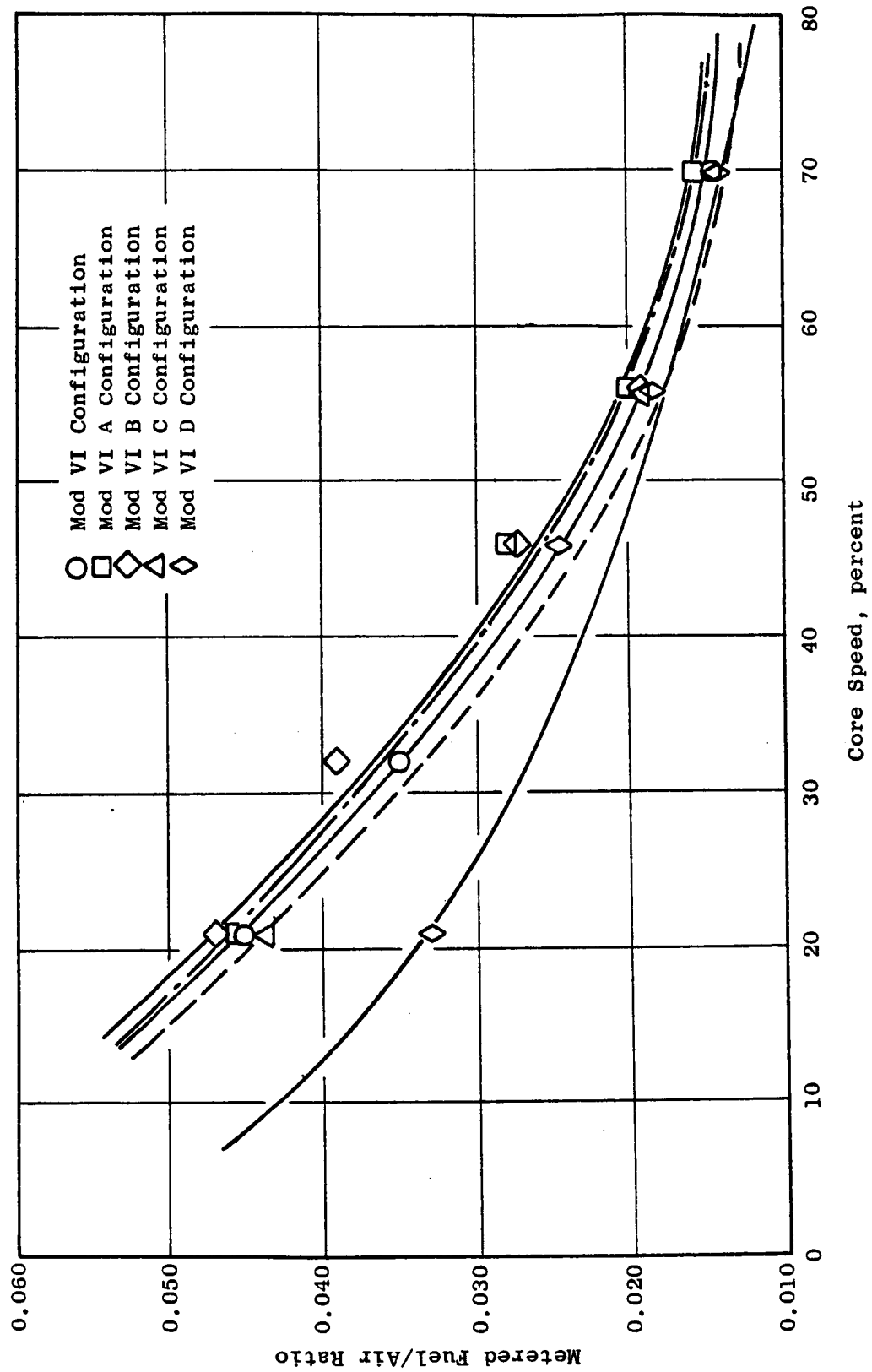


Figure 2.3-15. E<sup>3</sup> Sector Combustor Main Stage Crossfire Ignition Tests.

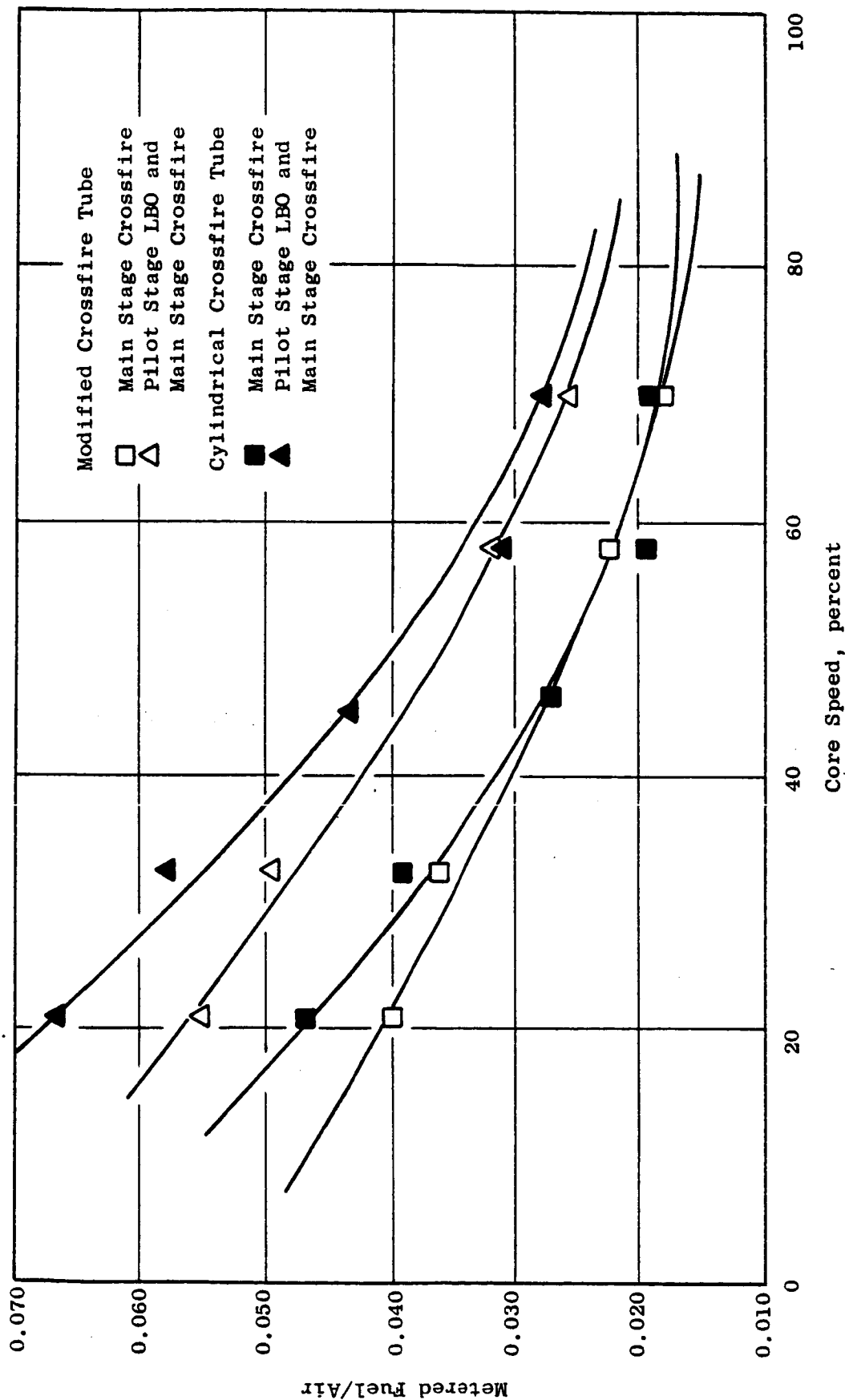


Figure 2.3-16. E<sup>3</sup> Sector Combustor Ignition Test.

ground-start cycle is shown in Table 2.3-V. The pilot stage ignition performance for the new ground-start conditions is excellent in terms of fuel/air ratios required for light-off of the combustor (Figure 2.3-17). At 31.5% core speed, which is the speed at which engine start is expected, the full propagation fuel/air ratio is approximately 0.0130, which is well below the fuel/air ratio of 0.0155 provided based on the flow schedule. Hence, ignition performance of the Mod VI sector combustor is considered satisfactory.

Table 2.3-V. June 1981 Revised Start Cycle.

Core Speed, PCNHR (%)	P3, atm	T3, ° R	Wc, pps	fm
16	1.0	536	0.63	0
24	1.0	558	0.90	0
28	1.0	570	0.98	0
40	1.0	648	0.88	0.0164
52	1.0	740	0.88	0.0173

Activity in the sector program was next directed at evaluating the ignition performance of the sector at various altitude and Mach number operating conditions simulating windmilling engine restart. The flight envelope investigated with key operating points is shown in Figure 2.3-18. The selected combustor inlet operating conditions to be evaluated, which simulate windmilling operation of the engine at altitude, are shown in Table 2.3-VI, and were provided by the E<sup>3</sup> Aerothermo Performance group as a best estimate of the true E<sup>3</sup> combustor inlet conditions.

Based on preliminary data analysis, the results of this last component test were very encouraging. Pilot and main stage ignition performance appear satisfactory. Main stage ignition was accomplished below ground idle, and the Co and HC emissions levels at low-power operating conditions approach closely or meet the target levels. However, data analysis has not yet been completed to provide the final results.

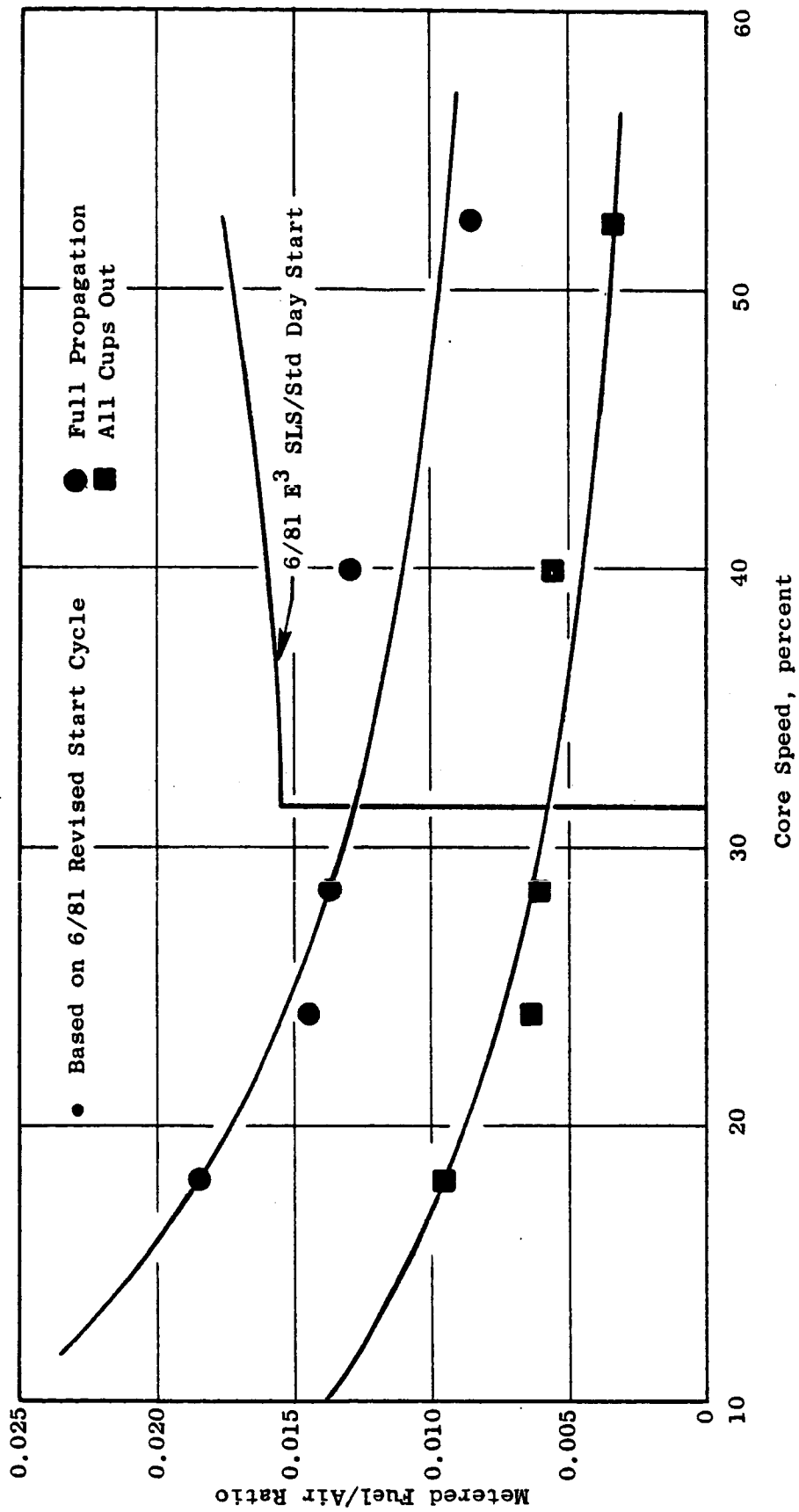


Figure 2.3-17. E<sup>3</sup> Sector Combustor Ignition Test, Pilot Stage Ignition Performance.

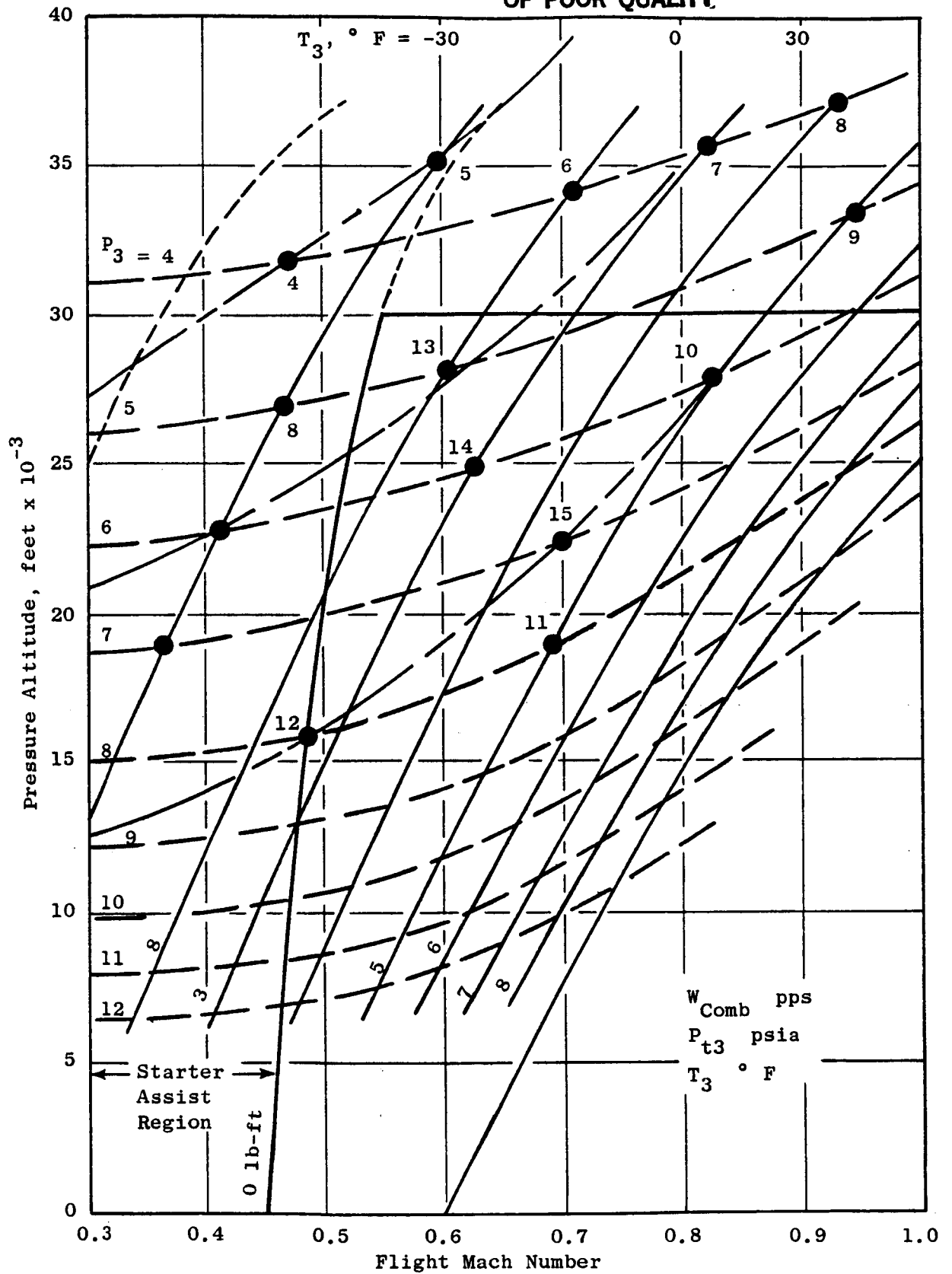


Figure 2.3-18.  $E^3$  Engine Windmilling Combustor Conditions.

Table 2.3-VI. Sector Combustor Altitude Relight  
Windmilling Conditions.

Test, PT	Alt, kft	M	P3, psia	T3, ° F	Wc, pps	T3, ° F	Wc, pps
1	19.0	0.37	7.0	10	0.17	amb	0.15
2	22.8	0.41	6.0	0	0.17	amb	0.15
3	27.0	0.47	5.0	-12	0.17	amb	0.15
4	32.0	0.47	4.0	-30	0.10	amb	0.09
5	35.0	0.60	3.5	-30	0.17	amb	0.15
6	34.0	0.71	4.0	-12	0.33	amb	0.30
7	35.5	0.83	4.0	0	0.50	amb	0.46
8	37.0	0.94	4.0	15	0.67	amb	0.62
9	33.0	0.95	5.0	30	0.83	amb	0.79
10	28.0	0.83	6.0	30	0.83	amb	0.79
11	19.0	0.69	8.0	40	0.83	amb	0.79
12	16.0	0.48	8.0	30	0.43	amb	0.41
13	28.0	0.60	5.0	0	0.33	amb	0.31
14	25.0	0.63	6.0	13	0.50	amb	0.46
15	22.4	0.70	7.0	30	0.75	amb	0.71

All of the core engine combustor hardware has been received except for the fuel nozzles. In order to determine the expected airflow distribution from the combustor assembly, the components comprising the assembly were individually airflow calibrated. The results obtained for the component effective flow areas are now being analyzed. Utilizing this flow data, estimates of core engine combustor airflow distribution will be calculated and compared to the flow distribution of the Mod VII configuration.

#### Work Planned

Results from the most recent development tests will be reviewed and, based on the findings, the core engine combustor will be modified to provide the desired flow distribution. Next, the core engine combustor will undergo a series of component tests to evaluate its performance prior to release to the core engine buildup.

#### 2.3.4 Full-Annular Test

The objective of the full-annular combustor test program is to develop the emissions and performance features of the E<sup>3</sup> double-annular combustor design utilizing technology from the GE/NASA Experimental Clean Combustor Program (ECCP) and the GE/NASA Quiet Clean Short-Haul Experimental Engine (QCSEE) program as well as evolving new technology. The key objective of this task is to release a combustor to the core and ICLS engines which has verified in component tests that it will meet the emissions and performance goals of the E<sup>3</sup> program.

To accomplish this task, two different types of full-annular combustor tests are being conducted: (1) high pressure tests to develop the emissions, performance, and durability characteristics of the combustor at various simulated engine-operating conditions from idle to takeoff, and (2) atmospheric-pressure combustor tests to develop the required combustor exit temperature distributions and ground-start capabilities. The altitude relight capabilities of promising combustor configurations will be evaluated in accompanying sector combustor tests. Past experience has shown that altitude relight performance results obtained in sector combustor tests are quite representative of full-annular combustor altitude relight performance.

Initially, cold-flow calibrations of the E<sup>3</sup> combustor test hardware are performed prior to initiation of the combustion tests to ensure that the overall combustor pressure drop is within limits and that the various dome and liner cooling airflows are distributed as intended. Following the verification of the combustor design flow area, the initial full-annular test is conducted at atmospheric pressure to provide data on ground-start characteristics, pattern factor, and profile factor. No emissions data are obtained during these tests. This type of atmospheric testing has been the main tool for developing the excellent exit-temperature performance of other General Electric combustors. High pressure tests are then conducted to determine the emissions levels and other performance characteristics of the combustor test configuration over a range of simulated engine power settings from idle to takeoff.

These high pressure investigations will be conducted primarily at simulated standard day engine operating conditions representing ground idle, takeoff, climb out, and approach conditions commensurate with the specified EPA landing/takeoff cycle. In addition, combustor performance at other simulated engine power conditions is investigated as part of the tests. At certain test conditions, variations of the fuel-flow split between the two combustor annuli are investigated to determine the effects of fuel biasing on emissions and combustor metal temperatures.

Upon selection of the final design for engine installation, all of the design features evolved in the development program will be incorporated in the core engine combustor. This hardware will then undergo complete evaluation of all facets of combustor operation including ignition, emissions, and performance. This combustor will be released to the core engine upon satisfactory completion of the tests.

Full-annular test activities were directed toward providing component test data to evaluate ignition performance and exit temperature patterns for the development combustor. Testing evolved into two phases. The first series of tests involved the continued evaluation of the rich main stage dome configurations to obtain a design that would provide satisfactory ignition of the main stage at core engine subidle speeds associated with ground start. The combustor configurations (Mods III, IV, and V) with the rich main stage dome

were evaluated for ground-start ignition and/or performance. Late in this reporting period, compressor and turbine component data became available which permitted the combustor design to be reverted back to the original lean main stage dome concept. Two more combustor configurations (Mods VI and VII) were tested to evaluate ignition, exhaust gas temperature distribution, and low-power emissions performance. At the conclusion of these tests, preparations were initiated to conduct component tests of the core engine combustor hardware.

Key hardware changes implemented for each combustor configuration are outlined in Table 2.3-VII.

The design modifications implemented in Mod III were directed toward improving ground-start ignition performance. Implementation of the combustor hardware featured in this configuration proved very effective in obtaining significant improvements in the main stage ignition characteristics. Successful ignition and full propagation of the main stage were obtained at simulated corrected core speeds as low as 32% PCNHR. A partial propagation of the main stage was obtained at 28% PCNHR. Ignition data were adjusted to true engine cycle combustor inlet pressure conditions using pressure effect characteristics determined from sector and full-annular combustor ignition testing at pressure. As shown in Figure 2.3-19, when adjusted for the combustor inlet pressure effects, it is estimated that the Mod III combustor configuration would achieve full main stage propagation within the ground-start fuel schedule at corrected core speeds at or above 45% PCNHR. During test, it was observed that at the lower simulated core speed operating points, hot combustion gases passing through the crossfire tubes were still being swept downstream upon discharging into the main stage annulus. Main stage ignition and initial flame stabilization appeared to occur in the plane of the main stage primary dilution. As the fuel/air mixture in the main stage is leaned out, the flame front propagates upstream and seats in the recirculating zone established by the swirl cup. At test conditions where main stage ignition occurred, the main dome swirl cup equivalence ratios were around 3.0 which is above the rich stability limit. At the plane of primary dilution, the equivalence ratios were near 1.0, which is considered ideal for ignition. This suggests that the crossfire tubes are located too far aft on the centerbody

Table 2.3-VII. Development Combustor Hardware Modifications.

Combustor	Pilot Dome	Main Dome	Centerbody	Outer Liner	Inner Liner
Mod III	Pilot dome cooling reduced	Swirl cup flow reduced Dome cooling reduced	Extended cross fire tube	Aft dilution increased	Aft dilution increased Eliminated Panel 2 dilution
Mod IV	Pilot dome cooling reduced	Swirl cup flow reduced Dome cooling reduced	Extended cross fire tube	Aft dilution increased	Aft dilution reduced Panel 2 dilution added
Mod V	Pilot dome cooling reduced	Swirl cup flow reduced Dome cooling reduced	Reduced primary dilution thimble	Added Panel 2 dilution	Reduced primary dilution thimble
Mod VI	Pilot dome cooling reduced	Swirl cup flow increased	Original cross fire tube	Panel 2 removed Aft dilution reduced	Aft dilution reduced
Mod VII	Pilot dome cooling reduced	Swirl cup flow increased	Original cross fire tube	Panel 2 removed Aft dilution reduced	Panel 2 dilution increased

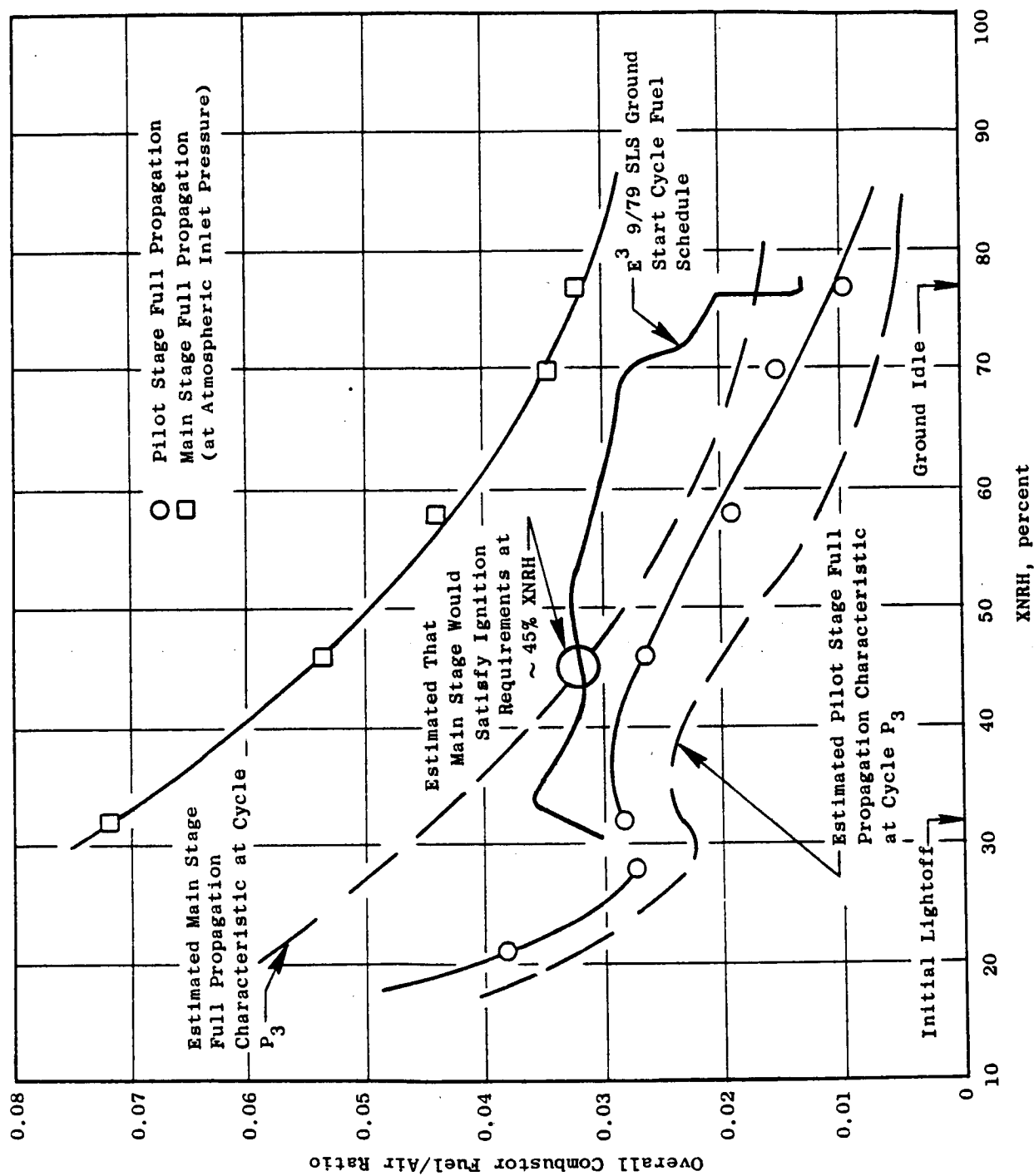


Figure 2.3-19. E³ Development Combustor Mod III Ground Start Ignition Pilot and Main Stage Full Propagation.

structure, since the ignition source and ideal combustible fuel/air mixture do not come together until the primary dilution plane. It appears that a substantial improvement in main stage ignition characteristics could be obtained if it were possible to move the crossfire tubes (ignition source) closer to the main stage swirl cup.

To enhance penetration of the pilot flame into the crossfire tube, dome cooling at the centerbody joint was blocked locally. In general, hardware modification produced no significant change in the ignition and lean extinction characteristics of the Mod III combustor configuration. However, one significant result did emerge: substantial improvements were achieved in pilot and main stage ignition and in lean extinction characteristics at test points where the effect of increased combustor airflow was evaluated. This result is most likely associated with better fuel atomization and fuel/air mixing created from higher swirl cup airflows and pressure drop offsetting the adverse effects of higher dome velocities. Estimated mainstage ignition performance at actual engine combustor inlet pressure is presented for the standard and high flow operating conditions in Figure 2.3-20. These results indicate that, without compressor bleed during ground startup, the main stage could be successfully crossfired at corrected core engine speeds below 40% PCNHR.

The combustor was next modified in order to obtain further improvements in the main stage ground-start characteristics, as well as trimming the exit temperature profile.

Ground-start ignition test results for the Mod IV combustor configuration are compared with results for the previously tested Mod III configuration in Figure 2.3-21. The pilot stage full-propagation and one-cup-out characteristics remained unchanged. This was expected, as there were no hardware modifications made to the pilot stage annulus. However, some deterioration in main stage full-propagation and one-cup-out characteristics did result. Some reduction in the lean stability margin was also observed. Despite the fact that some deterioration in the main stage ignition characteristics did occur, the Mod IV results tend to indicate that small amounts of inner liner Panel 2 dilution can be used without seriously impacting main stage ignition.

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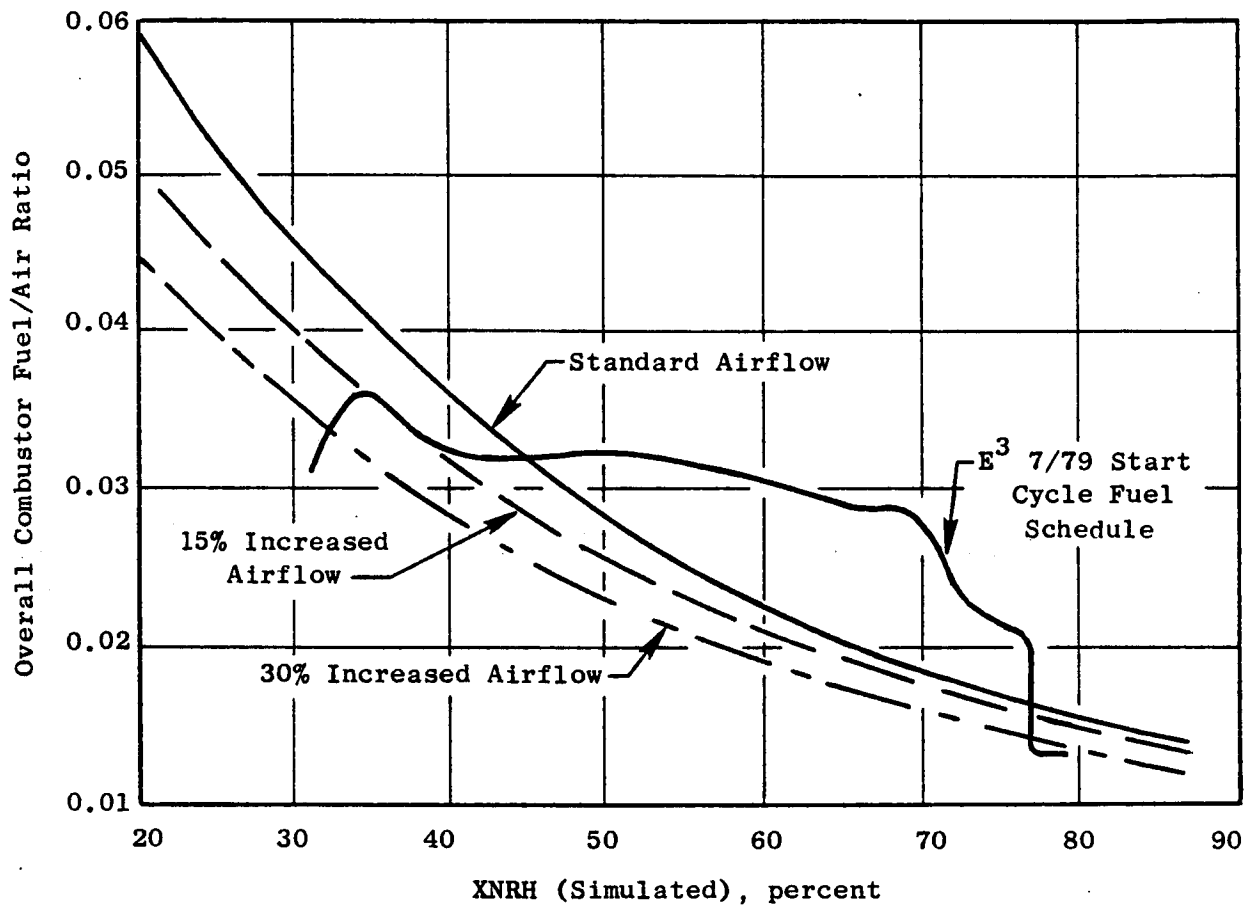


Figure 2.3-20. E<sup>3</sup> Development Combustor Ground Start Ignition Test, Mod III Estimated Results at Pressure (Main Stage Fuel Propagation).

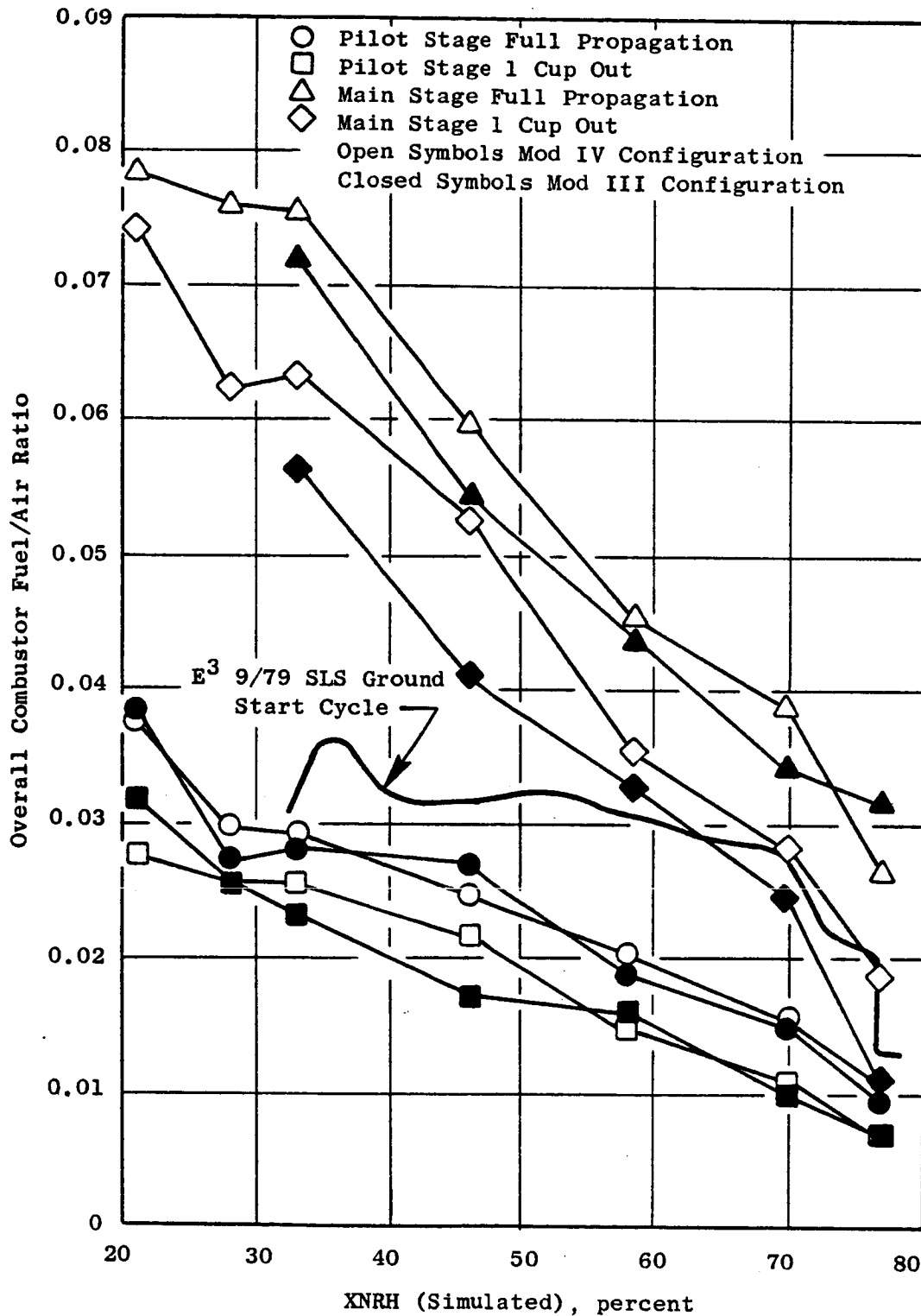


Figure 2.3-21. Ground Start Ignition Comparison for  $E^3$  Development Combustor Mod IV and III (Atmospheric Pressure).

Mod V modifications were intended to further enrich the main stage dome in order to improve ignition characteristics and attenuate the exit gas temperature profiles, especially in the pilot-only mode of operation.

Ground-start ignition test results for the Mod V combustor configuration are compared to the Mod IV ignition test results in Figure 2.3-22. As observed from the figure, some minor improvements in main stage ignition characteristics over those demonstrated with the Mod IV configuration were obtained. However, main stage ignition performance is not quite as good as that demonstrated with the Mod III configuration. Based on these results and on estimates of the expected improvements resulting from operation at actual engine cycle combustor inlet pressures, it is estimated that full propagation of the main stage could be achieved at a corrected core engine speed of 50%. This compares to a desired core engine starting speed of 45% or less. Despite the introduction of some outer liner Panel 2 dilution, pilot stage ignition characteristics remained unchanged.

Results from the performance test of the Mod V combustor configuration are presented in Figure 2.3-23. The average profile at the the 50/50 fuel split is generally within the established limit and is reasonably flat. However, the maximum profiles are sharply peaked inward and exceed the established limit by a considerable amount. It is observed from Figure 2.3-24 that maximum profiles less than 1.0 were obtained at all of the pilot-only subidle operating conditions investigated. These levels are significantly lower than levels measured during performance testing of the Mod I configuration at the same operating conditions. This improvement is attributed to the outer liner Panel 2 dilution featured in the Mod V configuration. The significance of this result relates concern over the effects on turbine survival when adjusted to the sharply outward peaked temperature profiles resulting from pilot-only operation. Any attenuation in these profiles would be very beneficial to turbine life.

Based on new evidence (confirmed by test data) that the combustor ground-start sequence could be accomplished with the pilot dome only fueled, this series of tests was terminated. Thus the combustor was reverted back to the original lean dome configuration, with some changes incorporated to further improve performance.

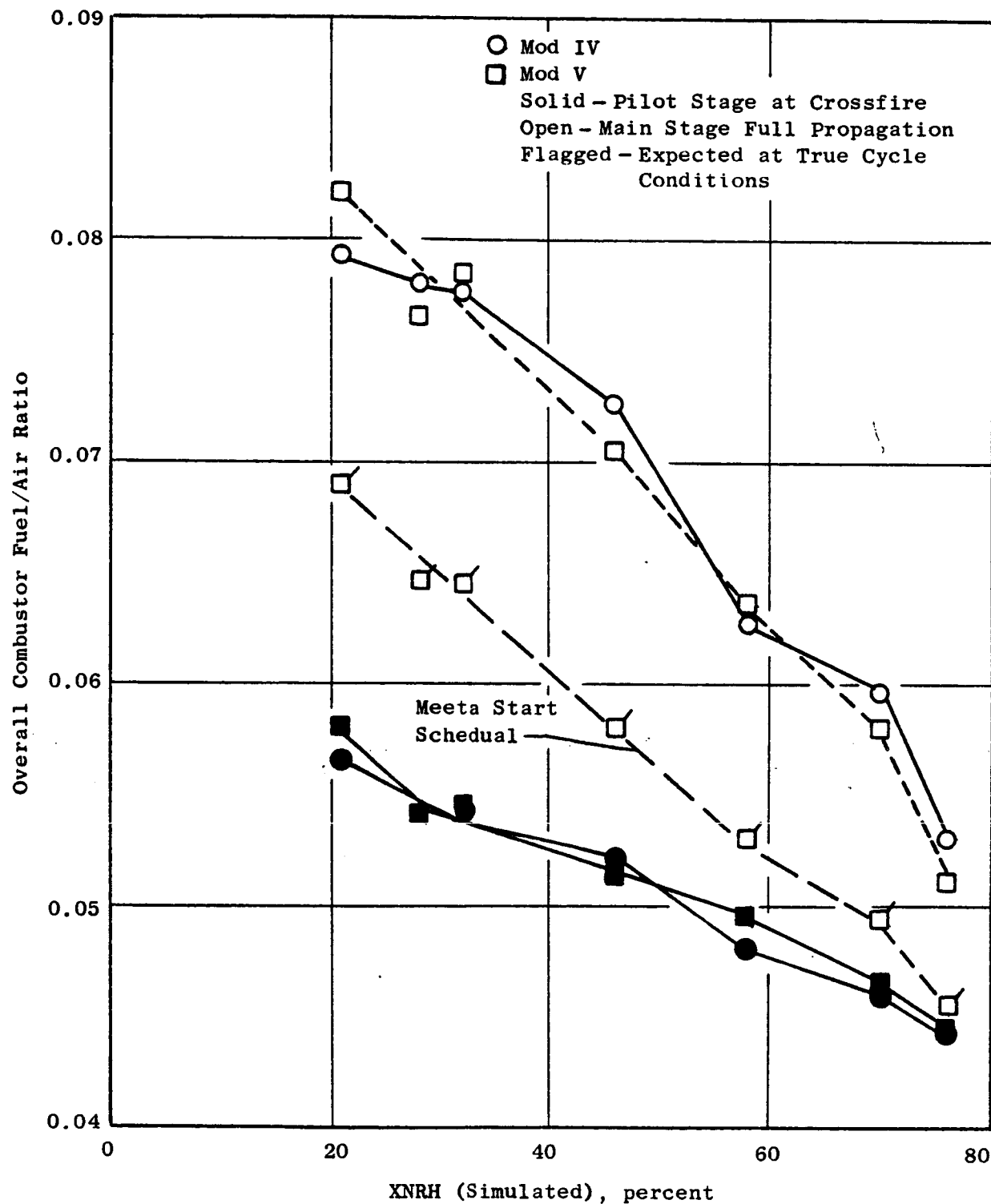


Figure 2.3-22. Ground Start Ignition Comparison for E<sup>3</sup> Development Combustor Mod IV and Mod V (Atmospheric Pressure).

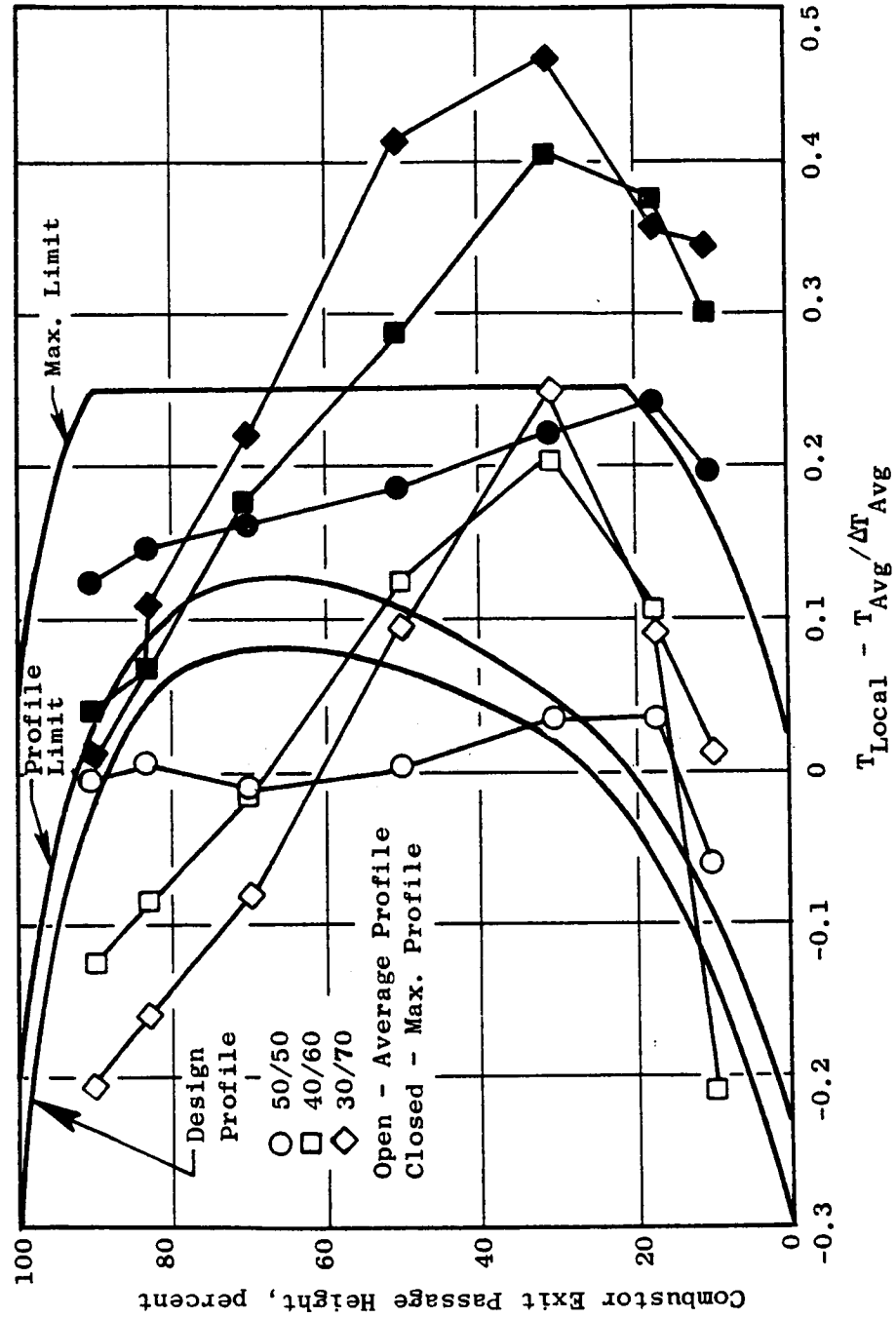


Figure 2.3-23. E<sup>3</sup> Double Annular Dome Development Combustor Exit Temperature Performance, Mod V at SLTO.

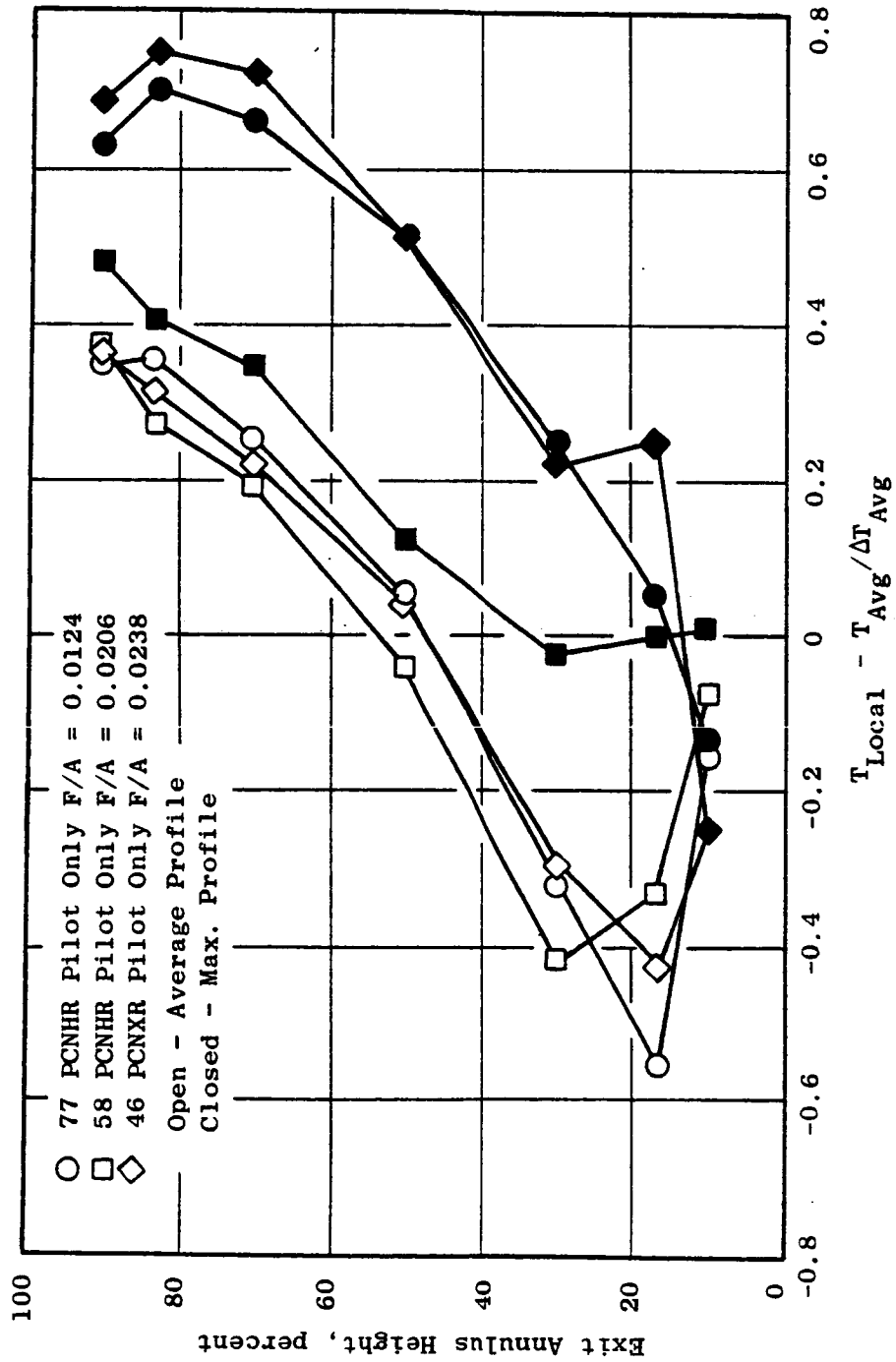


Figure 2.3-24. Mod V Development Combustor Exit Temperature Distribution, Pilot Stage Only.

Next, the Mod VI was evaluated for ground-start ignition and main stage crossfire characteristics with and without compressor bleed along the revised E<sup>3</sup> ground-start operating cycle. As in past tests, the combustor inlet pressure was atmospheric.

Results from this evaluation are presented in Figure 2.3-25. As observed, the pilot stage ignition characteristics satisfy the fuel schedule requirements defined by the revised start cycle. Taking into consideration the improvements with pressure, the pilot stage is expected to demonstrate considerable ignition margin along the revised start cycle with or without bleed. Also observed from this figure are the main stage crossfire characteristics. Overall combustor fuel/air ratios of 0.030 or higher were required to successfully crossfire and fully propagate the main stage. These levels are above the fuel schedule defined in the engine operating cycle. However, a significant amount of improvement in the main stage crossfire characteristics would be expected at actual engine combustor inlet pressures, but the degree of improvement is not known at this time.

. The Mod VI combustor was subsequently tested for exit temperature profile characteristics. The results were disappointing in that pattern factor and profile results substantially exceeded the target levels. Posttest inspection revealed several discrepant hardware features, primarily in the dilution thimbles and emissions reduction sleeves. The development combustor hardware was refurbished and additional minor changes incorporated prior to retest as the Mod VII configuration.

Exit temperature performance evaluation of the Mod VII combustor was conducted at simulated sea level takeoff operating conditions with pilot-to-total fuel splits of 0.5, 0.4, and 0.3. Data were taken at operating conditions simulating 30% thrust at pilot-to-total fuel splits of 1.0, 0.5, and 0.4 and at 4% ground idle at pilot-to-total fuel splits of 1.0, 0.5, and 0.4. As in past tests, exit gas temperatures were measured with four rakes, each with seven C/A-type thermocouple elements. Traverse increments of 1.5° were taken at all test conditions.

Average and peak profiles determined at the simulated sea level takeoff operating conditions are presented in Figure 2.3-26. As seen from this

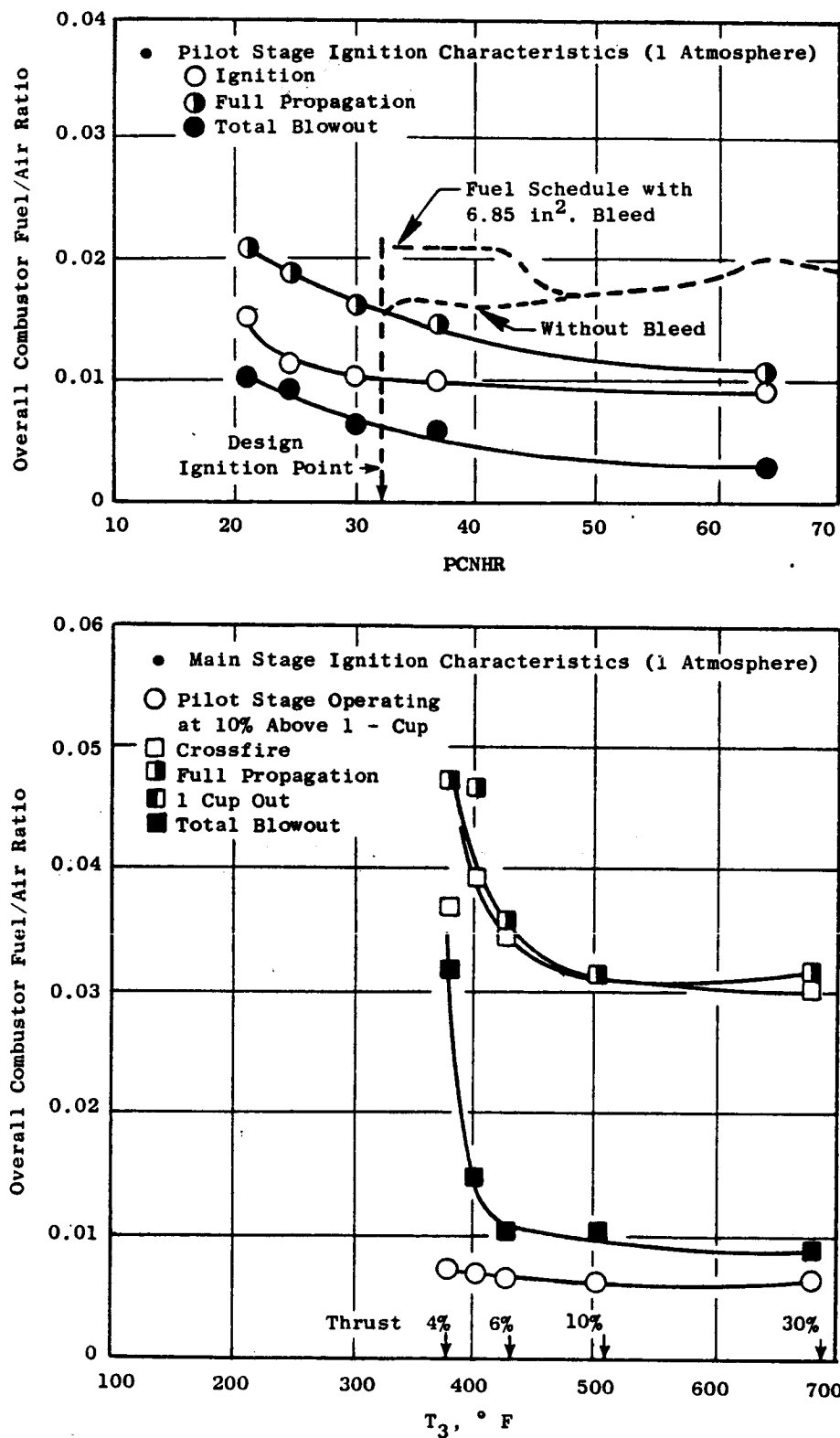


Figure 2.3-25. E<sup>3</sup> Development Combustor Mod VI Ignition Results.

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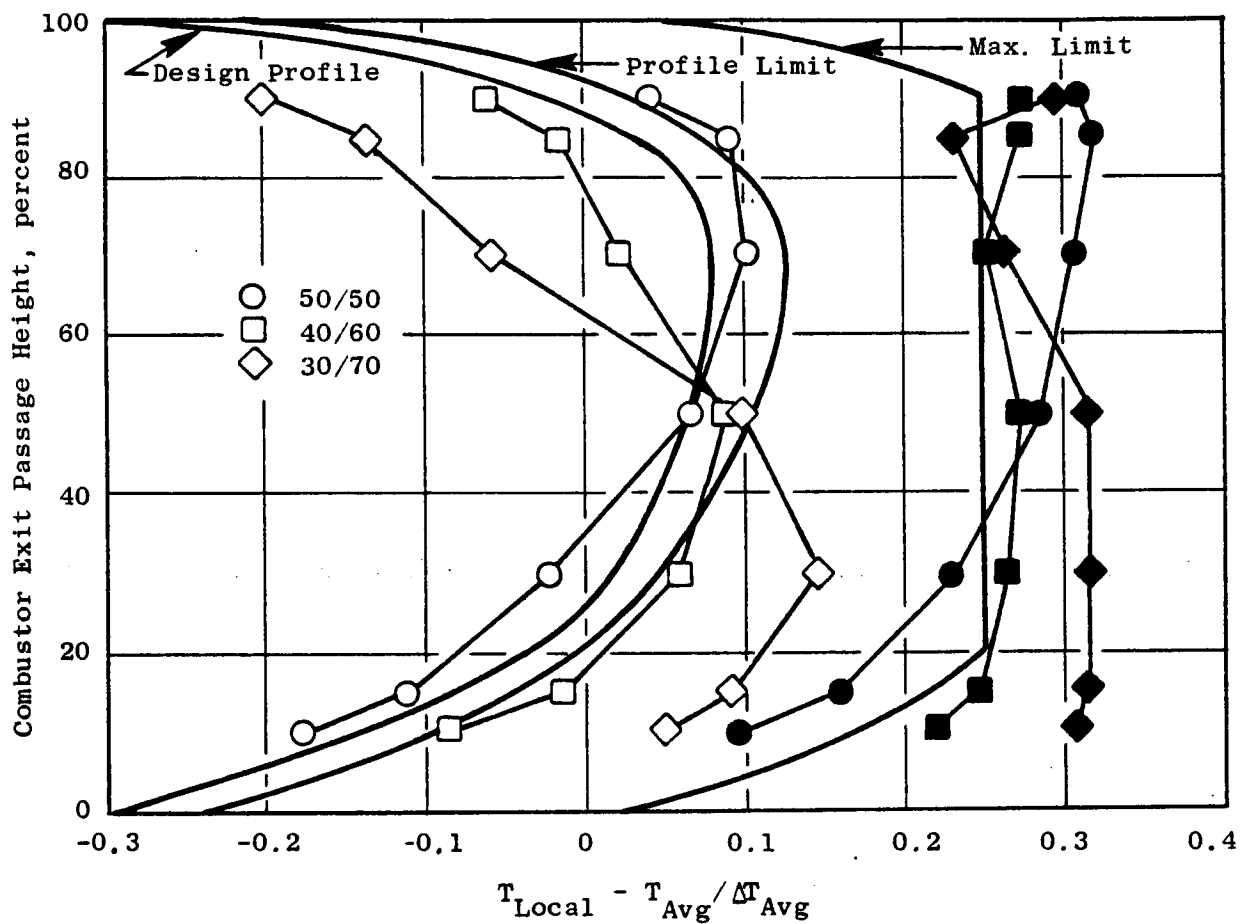


Figure 2.3-26. E<sup>3</sup> Double Annular Dome Development Combustor Exit Temperature Performance, Mod VII (1 Atmosphere).

figure, the design average profile was closely approached at a 40/60 design fuel split. The best peak profile occurred at the design 40/60 fuel split with a pattern factor of 0.275. This represents a significant improvement over the Mod VI performance, although still slightly exceeding the design goal of 0.250. The average profile at this fuel split was inner peaked and slightly exceeds the design limit at the hub. Average and peak profiles determined at simulated lower power operating conditions are presented in Figure 2.3-27 for pilot stage only. It is observed from this figure that pattern factors of 1.25 can be expected from operation of this combustor design in the pilot-only fuel staging mode. A pattern factor of approximately 1.50 was determined for the earlier Mod I configuration at simulated 6% ground idle operating conditions.

Based on the very promising performance test results, the Mod VII combustor was then tested at pressure in order to evaluate ignition performance at true ground-start cycle conditions and determination of the emissions characteristics at low power operating conditions.

Ignition performance was evaluated by observing the response of two thermocouples attached to the outer and inner elements of the five gas sampling rakes installed at the combustor exit.

The results are presented in Figure 2.3-28. They demonstrate that the pilot stage satisfies the engine requirements with margin and that the main stage can be ignited at core engine speeds above 60% PCNHR. Ignition of the main stage above ground idle will require fuel/air ratios approximately 30% above the scheduled fuel/air ratio.

Emissions data were obtained at engine operating conditions duplicating 4% and 6% ground idle as well as simulated approach (30%  $F_N$ ) power. Results from this portion of the test are still being analyzed.

#### Work Planned

Following flow calibration and assembly of the core engine combustor, a series of component tests will be conducted in order to determine the core

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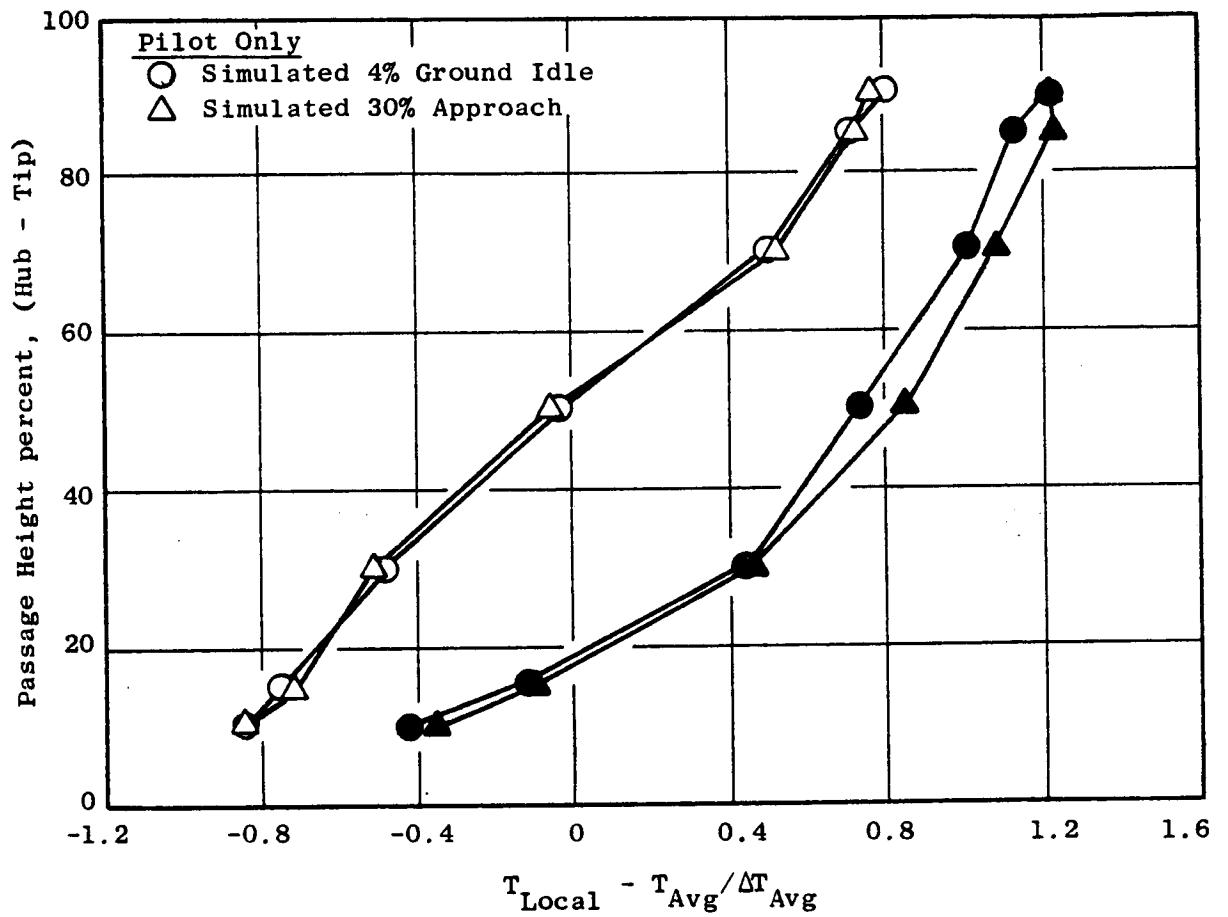


Figure 2.3-27. Mod VII Development Combustor Exit Temperature Distribution, Pilot Stage Only.

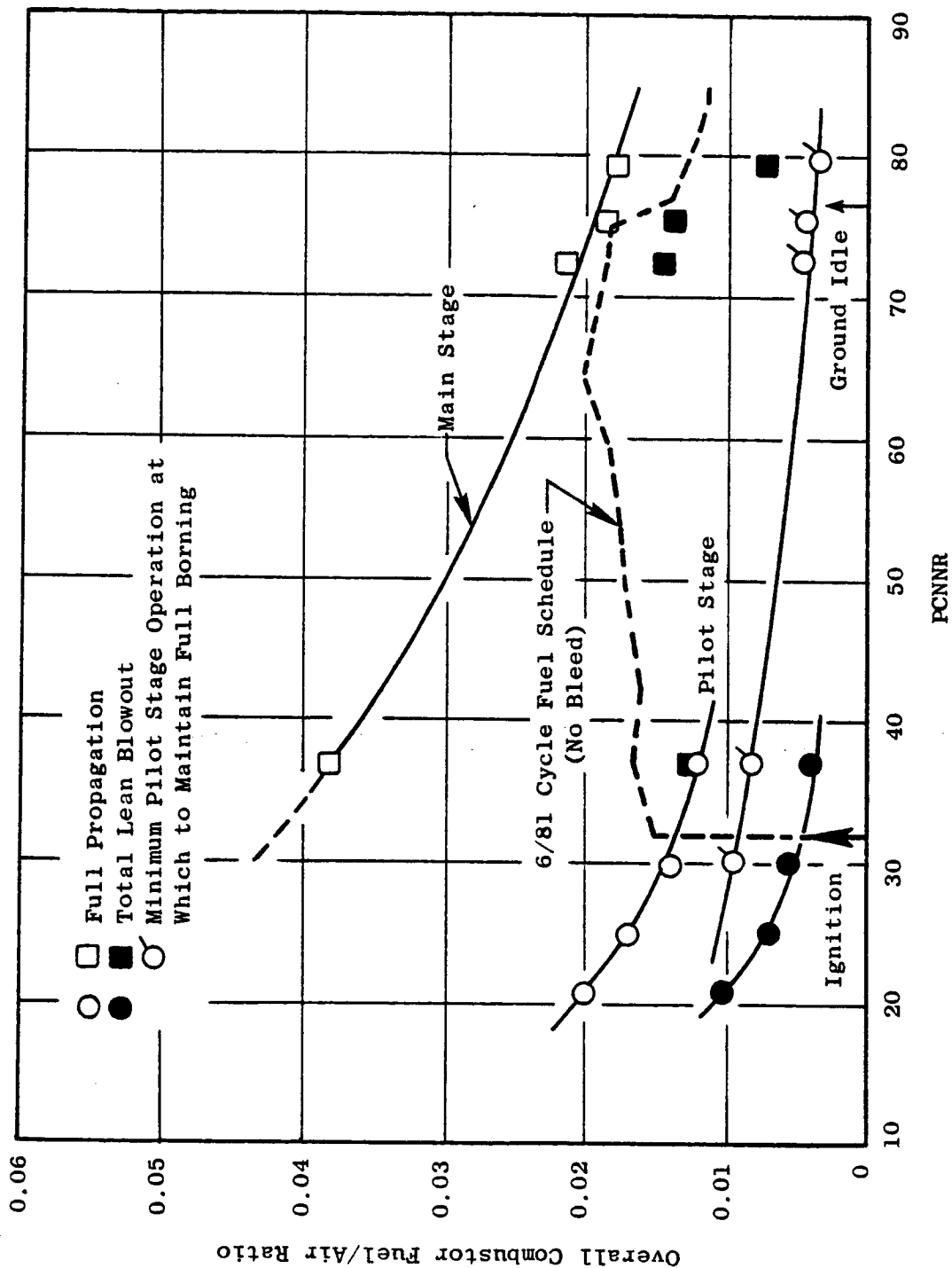


Figure 2.3-28. E<sup>3</sup> Development Combustor Mod VII Ignition Results at Pressure.

engine combustor performance. Testing will include evaluation of ignition and exit temperature distribution at atmospheric pressure followed by tests to measure ignition, metal temperatures, and emissions at combustor inlet pressures matching or approaching true engine conditions.

#### 2.3.5 Combustor Fabrication

Primary activity under this task involved procuring the hardware required for the core engine combustor. Combustor components that were on hold (such as inner and outer dome assemblies, centerbody, inner and outer support liners, and dilution eyelets) were released for manufacture following release of the final aerodynamic design definitions in May 1981.

These components have been manufactured and are currently undergoing extensive flow checking plus some minor rework. Overall hardware quality is excellent and the proper fit-up of the various components was achieved. The core engine combustor will be assembled and instrumented in October 1981, and component testing will be conducted.

All auxiliary combustor hardware items, such as fasteners, seals, and ignition and fuel system components have been inventoried and are available for engine buildup.

Significant manufacturing delay has occurred in the engine fuel nozzle manufacture. After manufacture of the initial engine set of fuel nozzles, internal contamination was detected by X-ray. This necessitated disassembly and flushing of the valve bodies and remanufacture of the fuel nozzle inlet tubes. Delivery of the initial set of fuel nozzles is now targeted for early October. This will not adversely impact initial testing of the core engine combustor, since the slave test rig nozzles can be utilized in the first test phase.

#### Work Planned

Complete final assembly of the core engine combustor and deliver to the engine buildup area late this year.

## 2.4 HIGH PRESSURE TURBINE

### Overall Objective

The objective of the HPT effort is to develop, evaluate, and demonstrate an efficient two-stage turbine. The turbine design incorporates features that provide the best balance of efficiency and direct operating costs while achieving required component-life requirements.

Performance achievements will be aimed at developing high turbine efficiency using moderately loaded airfoils. The HPT efficiency goal for the fully developed FPS is 0.924 at Mach 0.8, 35,000 feet altitude, standard day, maximum cruise power setting. Additionally, the turbine incorporates an active clearance/control system to achieve and maintain closer operating clearances for enhanced performance, particularly in climb and cruise operation.

### Development Approach (Reference WBS 2.4 Schedule Sheet)

The overall program plan for the HPT is to establish a turbine mechanical system and configuration that will achieve the projected levels of turbine efficiency and mechanical integrity. The aerodynamic design studies, initiated in March 1978, are devoted to the design for the air turbine and the aerodynamic airfoils definition for the core and the ICLS engine. In November 1978, an Intermediate Design Review was presented for the overall air turbine test program, the aerodynamic blade and vane airfoil definition, and the mechanical and heat transfer designs. In March 1979, the Preliminary Design Review was presented and approved for the aerodynamic, mechanical, and heat transfer designs.

The detailed mechanical design began in April 1979 and consisted of an 18-month effort to integrate the experience gained from the materials program, heat transfer cascade tests, air turbine tests, and preliminary mechanical and systems design. The High Pressure Turbine Design Review was presented to NASA on October 10, 1980, and was approved in December 1980. The review consisted of a presentation of all the technological disciplines associated with the turbine, i.e., heat transfer, mechanical, aero, and systems review. Upon NASA's approval of the design, the balance of the turbine components not yet released (as an advanced release) were authorized for manufacture. One set of hardware



will be purchased which also will be used for both the core and ICLS engine testing. Adequate spares have been ordered for flowpath components. Fabrication and manufacturing interface with vendors have continued within this reporting period.

Components will be instrumented for the core and ICLS engine tests for engine monitoring and safety (all rotor instrumentation shall be used during core engine tests only). Rework drawings necessary for instrumentation have been issued, and manufacturing is in process of completion.

In the present manufacturing cycle, all rotor hardware (except Stage 1 and 2 blades) are being delivered within scheduled requirements. These requirements are based on Evaluation Engineering's schedule for completing the work necessary for instrumentation application, assembly with dimensional checks, balancing, and, finally, engine level assembly.

Major efforts by the mechanical engineering group during this reporting period were as follows:

- Submitted the Detail Design Report to NASA for review
- Completed the residual life fracture mechanics analysis for all rotating components manufacture from powder material. This extensive analysis considered residual life calculations using current GE statistical techniques.
- Progressed in improved delivery for all hardware. Presently, all structure static and rotating components are delivered or are in progress of completion.

Although progress has been made in all schedule deliveries, the flowpath components remain the limiting items. These parts, namely Stage 1 and 2 nozzles and Stage 1 and 2 blades, are from 2 to 4 weeks behind schedule.

The thermal barrier coating program achieved a major milestone goal with the successful completion of a 1000 "C" cycle engine test (CF6-50 engine). The thermal barrier coated turbine parts consisted of Stage 1 and 2 nozzles and Stage 2 blades. This test demonstrated the feasibility and application of thermal barrier coated turbine parts for use in engine systems.

Based on thermal shock tests and sprayability parameters, a powder source has been selected for the engine hardware for the ceramic shroud program.

Parametric studies have resulted in identification of the precise processing to be used in the manufacture of the superpeg configured shrouds for E<sup>3</sup> tests. Although an NDE (infrared) techniques has been identified based on test panels, its applicability to engine hardware still needs to be evaluated.

#### 2.4.1 HPT Aero Design Analysis

##### Technical Progress

During this reporting period, posttest analysis of the air turbine rig data was completed. Analysis of the data confirms the previously quoted level of efficiency. A turbine map was generated for inclusion in the cycle deck.

Support was provided to the heat transfer and mechanical designers. This support was primarily to assess the impact on performance due to hardware anomalies, assembly, instrumentation, and design changes.

The decision not to coat the Stage 1 vane airfoils with physical vapor deposition (PVD) environmental coating caused a reduction in trailing edge thickness from 0.965 to 0.762 millimeter. This reduction in trailing edge blockage will provide a slight performance improvement.

The effects of not coating some or all of the last three blade rows were investigated. In general, the positive effects of reduced trailing edge blockage will be counteracted by the negative aspects of lower throat aspect ratio. Reaction and incidence effects are mixed but small. Flow function will increase; impact on performance will be small.

The possibility of higher coolant flow rates due to (1) problems in casting Blade 1 trailing edge geometry and (2) more leakage flow around the Stage 1 shrouds where the laser clearance probes are mounted were studied. These items could result in an efficiency decrement of 0.1% if flows are as predicted.

Area measurements of Stage 1 nozzle segments indicate that the flow area is larger than design intent by as much as 1.5%. Further studies are underway to determine the impact on both aero performance and heat transfer.

### Worked Planned

During the next 6 months, it is planned to publish the rig performance report. Continued support will be provided to heat transfer and mechanical designers as needed. Buildup of the core engine will be monitored.

#### 2.4.2 High Pressure Turbine (HPT) Heat Transfer Design

##### Technical Progress

Extensive work continues to be performed in the area of the HPT heat transfer design. This work has been directed at completing the detailed design heat transfer analysis of the turbine and resolving problems of discrepancies in the hardware for the first engine to test.

The detailed work effort in the area of the HPT during the last 6 months is presented here.

##### Stage 2 Blade

In order to evaluate the life of the second stage blade at the critical sections below the 50% span, a detailed thermal model was set up to evaluate these temperatures. Results from this model will be used along with the rupture-life hours, combined with the relative vibratory-stress levels between sections, to predict minimum blade life at the critical airfoil location and span section. The effects of thermal, gas bending, and centrifugal loads will be combined with vibratory stresses to indicate minimum life at the critical blade section.

As part of the required analysis, a three-dimensional temperature analysis of the Stage 2 blade at the FPS maximum takeoff power condition was defined. Blade sections that were analyzed included the 50%, 30%, 25%, 20%, and 10% spans. This analysis takes into account the change in gas temperature as predicted by the detailed profile analysis performed early in the detailed design. Internal cooling temperature boundary conditions were changed to reflect the coolant temperature rise due to pumping and heat pickup. Coolant heat transfer coefficients were also changed to reflect the change in flow area and the 180° serpentine bend effects.

Presented in Figure 2.4-1 is a detailed thermal model and a few representative temperatures from each section. Also, bulk metal temperatures at each span are presented in an effort to show the temperature gradients between local metal temperature and bulk.

#### Rotor Cooling Flows and Pressures

In order to assure proper blade cooling flows, a detailed analysis of HPT rotor coolant flows has been conducted. Because of the differences between the FPS and the test engine cycle, the prime purpose of this analysis is to be sure the cooling flow distributions match the design intent flows.

The ICLS maximum takeoff cycle was used in this analysis. The turbine interstage pressures were defined for the 4% open Stage 1 throat area. This raised the first stage blade relative gas pressure and the second stage vane absolute gas pressure. With the ICLS cycle data and the turbine interstage pressures, the source and sink pressures for the HP rotor flows were available.

A detailed compressible flow model of the rotor was set up and matched with the air turbine test data in order to verify the various hole flow coefficients and pumping efficiencies. This flow model was used with the ICLS pressures and temperatures to evaluate the flows. Presented in Figure 2.4-2 are the detailed flows and pressures that can be expected in the core turbine.

#### HPT Rotor Forward Cavity Thrust Analysis

In order to maintain the life of the core engine thrust bearing, thrust load must be kept within design limits. One area that might cause an increase in the aft thrust is the pressure in the forward cavity of the Stage 1 disk. If the flowpath seal runs tight, inducer seal leakage will cause pressure in the cavity to rise, thereby causing an increase in the aft thrust on the rotor. If the flowpath seal runs open, there could be hot gas injection into the rotor cavity which results in high blade retainer temperatures. Thus, it is important that seal clearances be set so proper design clearances are obtained at high thrust power conditions.

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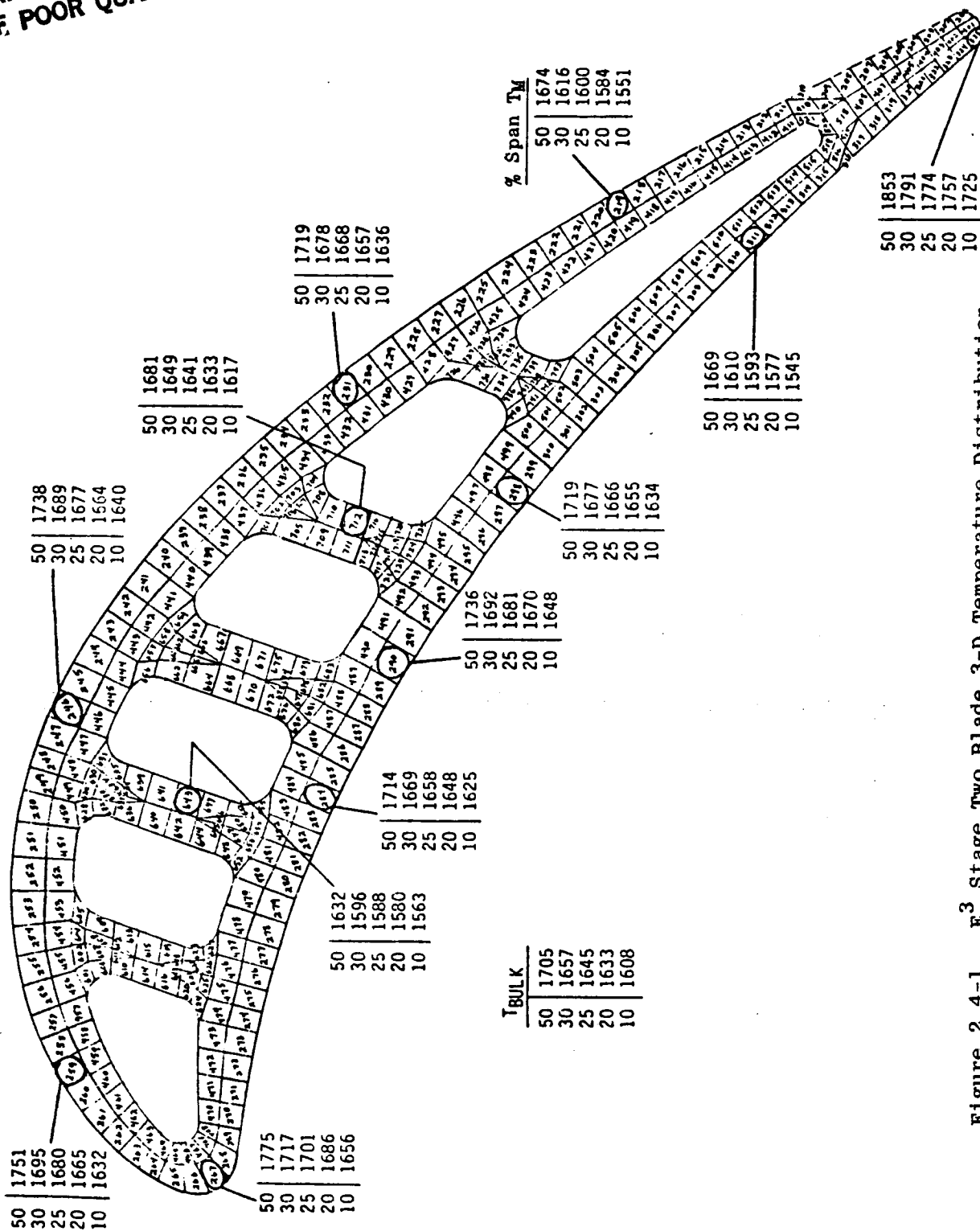


Figure 2.4-1. E<sup>3</sup> Stage Two Blade 3-D Temperature Distribution  
(50, 30, 25, 10% Span).

P<sub>3</sub> - 429.66 PSIA  
T<sub>3</sub> - 1085 °F  
W<sub>25</sub> - 150.43  
RPM - 13240

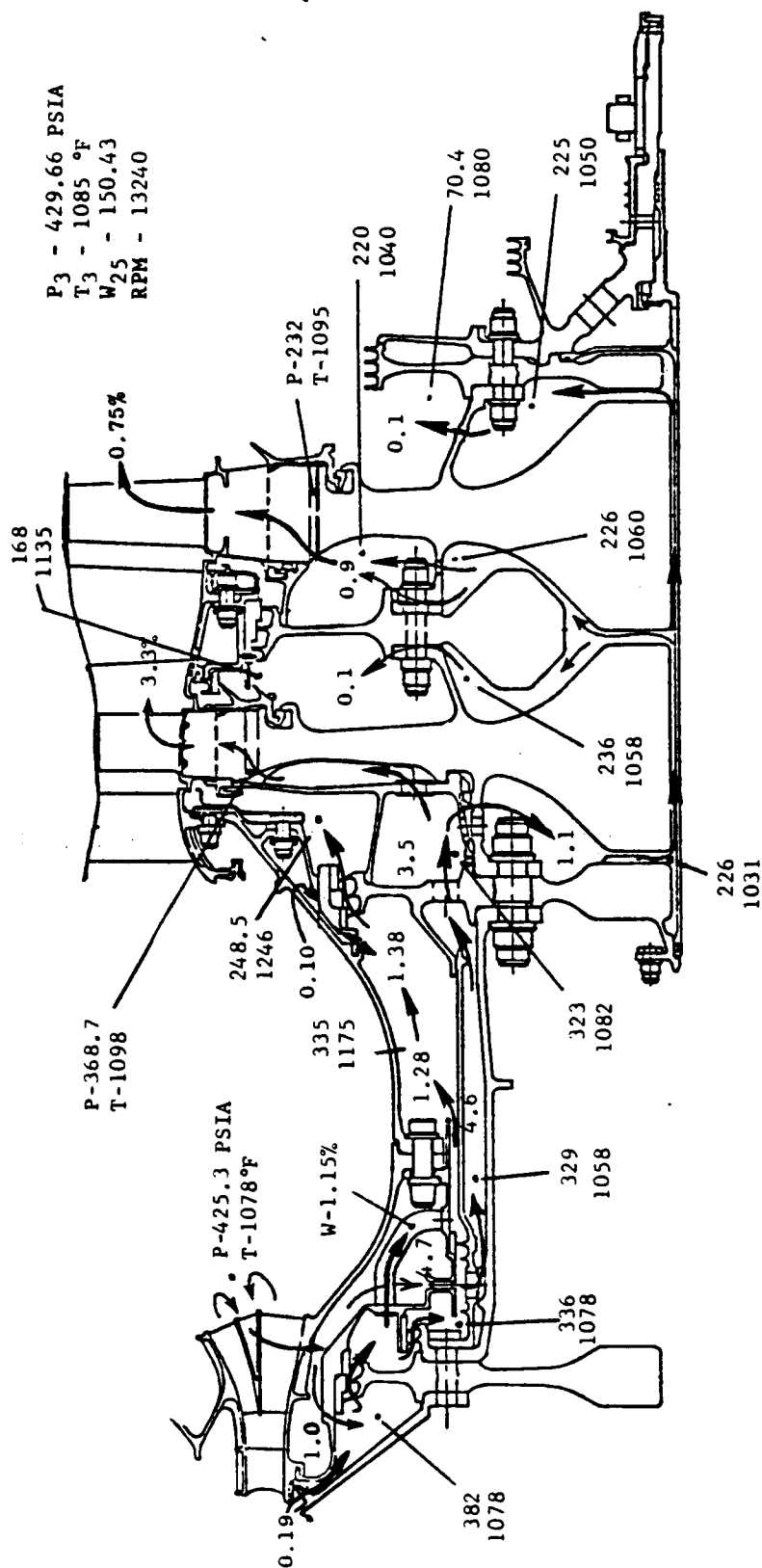


Figure 2.4-2.  $E^3$  HPT Rotor Flow Analysis ICLS Max. Takeoff  
86° F Day, + 4% A<sub>4.1</sub>.

In order to define the proper clearances, a detailed flow analysis of the inducer/rotor cavity and flowpath seal was conducted. The flowpath seal back pressure and hot gas ingestion characteristics have been defined. Results of the analysis are shown in Figure 2.4-3. At seal clearances below 30 mils, excess aft thrust on the rotor is experienced as the cavity pressure rises 5 psi above design level. At seal clearances above 125 mils, hot gases are injected into the cavity which results in a substantial increase in cavity temperature. Because of the possibility of hot gas injection, the maximum gap has been restricted to 80 mils. This occurs when the total gap of 200 mils is evenly split between the area under and over the angle wing. The angle wing tip thickness is 40 mils which leaves 160 mils to be split between the upper and lower gap.

This analysis was conducted for the nominal inducer seal clearance of 19 mils. On new engines, the inducer seal clearance will be lower since it has not sustained a transient rub. This will result in a slightly lower seal flow area and, thus, lower cavity purge flow. The maximum allowable flowpath seal gap may be reduced from 125 to 100 mils under this condition; but, since the maximum possible seal gap has been restricted to 80 mils, there is still a 20-mil gap margin for buildup tolerances. During the core test, the pressure and temperature in this cavity will be monitored to assure proper function of both the seal and purge systems.

#### Solid Metal Stage 1 Shroud Detailed Heat Transfer Design

During the detail design phase of the HPT, effort was made to secure the success of the thermal barrier coated (TBC) shroud design. It was decided, however, that a more conventional design was necessary as a backup configuration. Therefore, the preliminary heat transfer design was done for the solid metal film-cooled configuration. When the practicality of using clearance measurement probes in the core and ICLS engines became apparent, it was necessary to complete the detailed solid metal shroud configuration. The solid shrouds can be drilled to accept the clearance probe, whereas the TBC shrouds may be subject to spalling as a result of holes drilled through the TBC and into the metal backing. At the same time, this allows a back-to-back comparison of the TBC and the solid metal shrouds in the same engine.

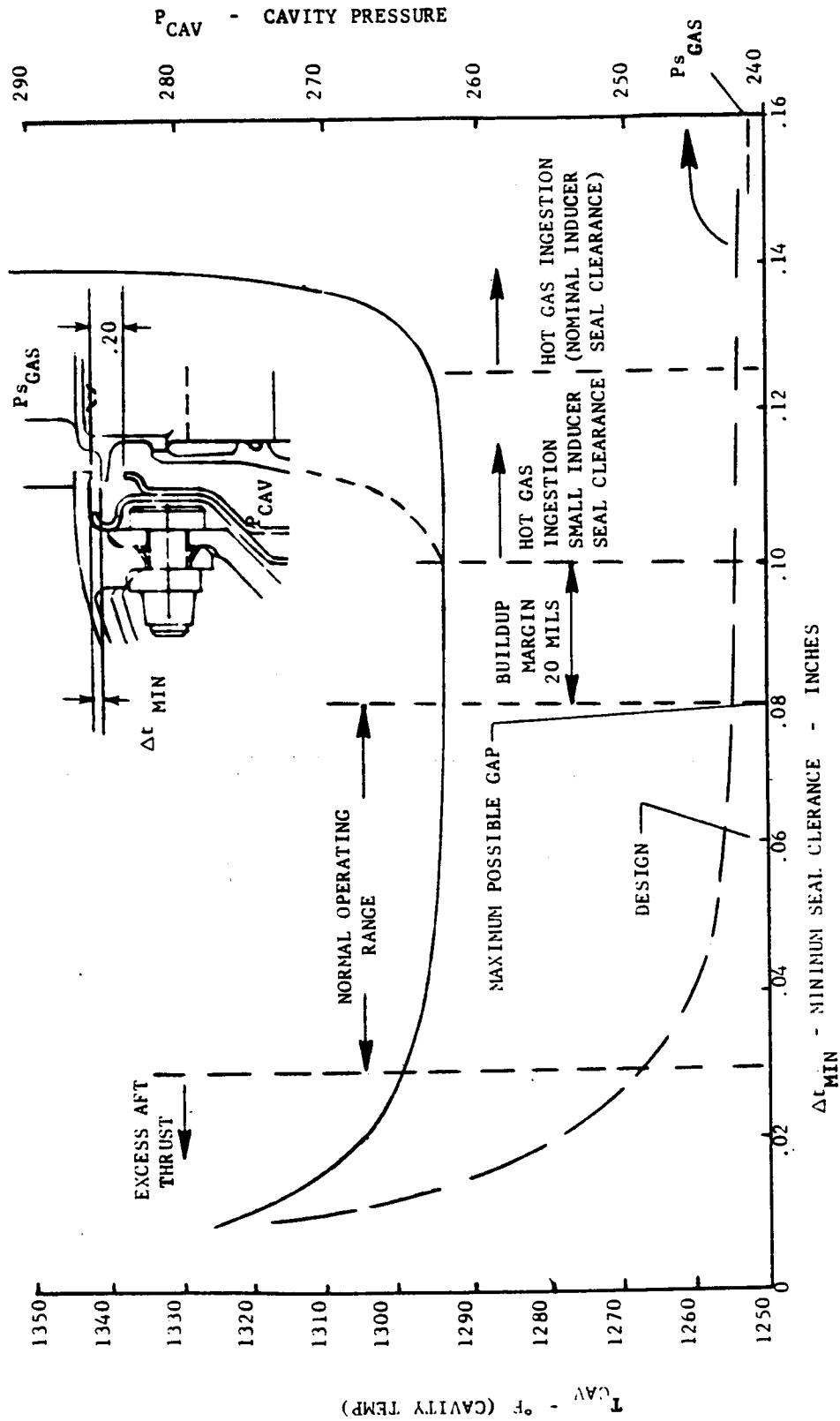


Figure 2.4-3. E<sup>3</sup> HPT Stage One Rotor Forward Cavity Seal Sensitivity.

The detailed analysis of the solid metal shroud was completed. The design (Figure 2.4-4) consists of the 360° impingement and multiple radial hole convection plus film. The main structure of the shroud is René 77 with a 60-mil rub coat of CoNiCrAlY flame sprayed on the gas surface. Impingement cooling is accomplished by use of 25-mil-diameter holes at an average spacing of 150 mils. The film hole convection is accomplished via 89 20-mil-diameter holes angled at 30° to surface. The increase length due to angling the holes improves convection and reduces film blow-off characteristics. The maximum surface temperature of the shroud reaches 1984° F which is an acceptable level for the CoNiCrAlY rub coat.

The design was done under the assumption that there would be a complete set of solid shrouds which would require 1.7%  $W_{25}$  for cooling and leakage. In the first engine to test, there will only be four solid shrouds in Stage 1 for the clearance probes. The net result will be a slight increase in flow to cover increased cooling for the solid metal shrouds and increased leakage around the clearance probes.

#### Engine Start Analysis

During the preliminary design effort, an engine-start analysis was completed. The analysis indicated that a 2100° F  $T_4$  temperature would be required to accel the engine to idle power. This high start temperature was caused by the quantity of compressor bleed air that was dumped overboard. Compressor bleed air was required during start in an effort to maintain a stall margin. The 2100° F  $T_4$  is not excessive for the HPT cooled flowpath components, but because of the low temperature drop in the HPT, it could present a problem for the LPT. This was accented when a simulated start was made utilizing the pilot combustor stage only. The maximum temperature in the LPT could not be tolerated; this required the combustor to be fired in both the pilot and main stage during start. With this information, the detailed analysis of the HP and LP turbines was completed.

Early in 1981, it became known from testing on the double-annular combustor that the main stage combustor could not be fired during start. In the same time period, compressor testing indicated that 30% bleed was not required

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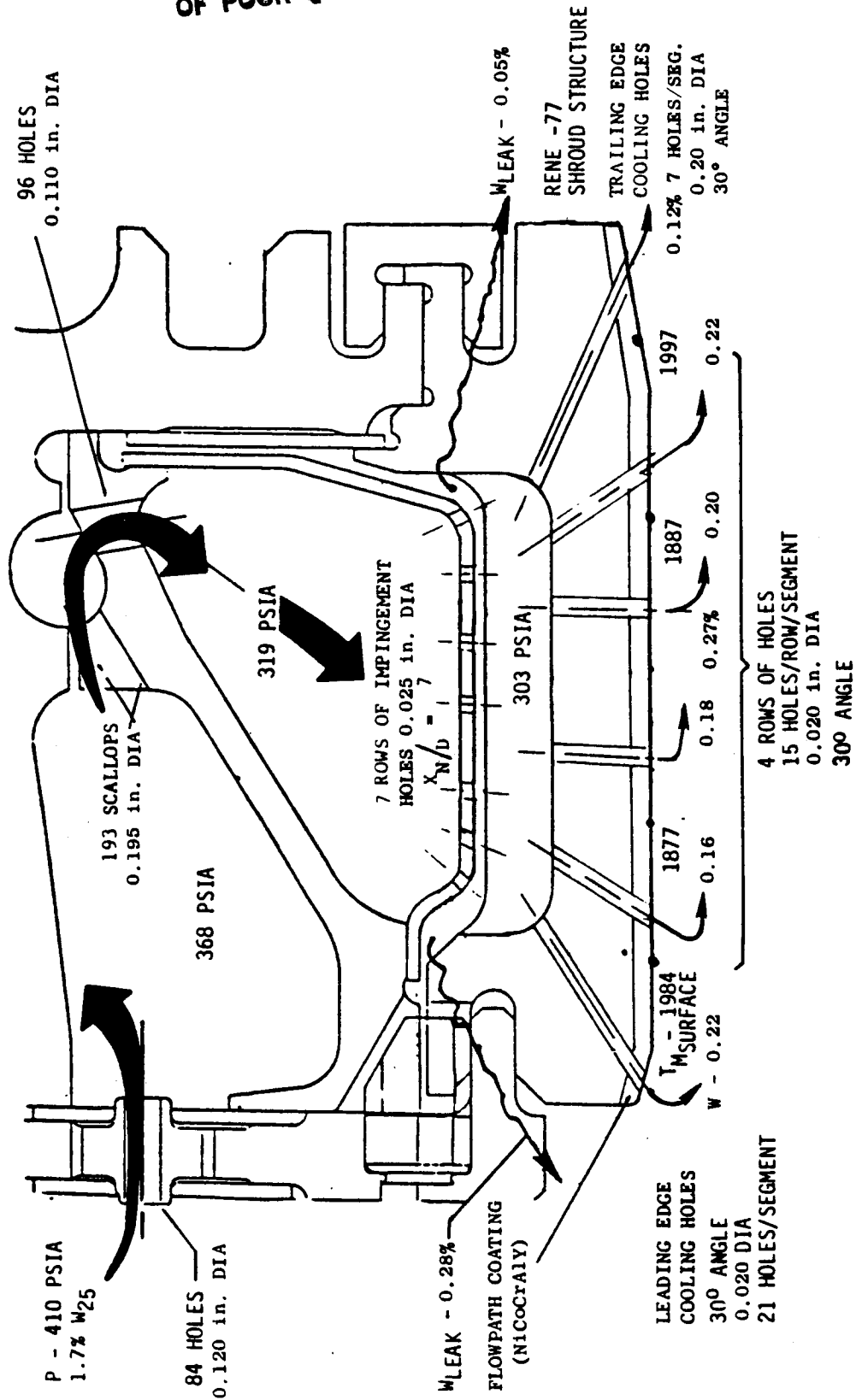


Figure 2.4-4. E<sup>3</sup> HPT Stage One Shroud Cooling Geometry Backup Design (Solid Metal).

in order to achieve the required stall margin. The E<sup>3</sup> HP air turbine tests also indicated that the efficiencies were 4 to 5 points higher than predicted in the engine start range. With these data in hand, the engine start analyses were revised. In order to keep the LP turbine gas temperature within limits, while starting the engine on the combustor pilot stage only, a cycle average T<sub>4</sub> temperature limit of 1750° F was defined. The results of the revised start analyses indicated that the engine could be started and that the maximum turbine inlet temperature is sustained for only 5 seconds. Also, engine start time was reduced to 50 seconds, well within the 1-minute limit. The LPT inlet temperature was reduced to a 1160° F cycle average. The start gas temperature transients at both the HP and LP turbine inlets are shown in Figure 2.4-5.

In order to evaluate the worst metal temperatures of both HP and LP turbines, a pseudotransient analysis of hot flowpath components was done. This analysis consisted of defining airfoil bulk and maximum metal temperatures under the high start gas temperature condition. The combustor exit maximum peak pattern factor of 1.26 and the circumferential average profile factor of 0.63 were defined from combustor testing of the original FPS design when only the pilot stage was lit. Since there was no E<sup>3</sup> data for the LPT inlet temperature profiles for the highly skewed combustor exit profile, CF6-50 data were used for the LPT inlet profiles. The double-annular combustor tested in the CF6-50 engine was started on pilot stage only. HPT exit data were correlated in terms of average LPT inlet, maximum measured, and compressor exit temperatures. These data yielded an LPT inlet maximum peak pattern factor of 0.27 and a circumferential profile factor of 0.21. Data from E<sup>3</sup> combustor testing and the CF6-50 test were used in the E<sup>3</sup> start analysis (Figure 2.4-6). The T<sub>4.0</sub> and T<sub>4.9</sub> margins were scaled down from the takeoff values since the combustor temperature rise is not as great during start. With the HP and LP turbine inlet temperature margins having been defined at 112° F and 88° F, respectively, design inlet gas temperatures for both HP and LP turbines were evaluated at 1852° F and 1246° F, respectively. When coupled with the HP and LP maximum peak pattern factor the maximum peak gas temperatures become 3631° F and 1474° F, respectively. These are the local temperatures that the HP/LP Stage 1 nozzle might expect to see during the start transient. An estimate of the worst metal temperatures that can be expected is given in Figure

2.4-7 along with the gradients between the bulk and maximum metal temperatures. The highest metal temperature to be expected in the HPT will occur on the second stage vane where the cooling effectiveness is down. In general, metal temperatures are significantly lower than the maximum power steady-state temperature expected on a hot day takeoff (Table 2.4-1). Temperature gradients between the bulk and maximum metal temperatures are higher, but since the maximum metal temperatures are 150° to 200° F lower, hardware life is only slightly effected. Gas bending loads and centrifugal loads are down. This also helps improve turbine life as affected by the start transient.

Because of all the complexities of the start analysis, no further work will be done in the area until core engine data is obtained. Data from the core test will be used to project the ICLS starting characteristics.

#### HPT Active Clearance Control (ACC)

In order to quantify the ability of the HPT ACC to control HPT clearances at cruise, a study was conducted to evaluate casing shrinkage using the fan air impingement cooling scheme. The ACC model was used in this analysis to define the clearance of the first and second stage rotor at various power settings between flight idle and maximum cruise.

The results of this analysis (Figure 2.4-8) indicate that a 16-mil Stage 1 rotor running clearance is possible over the complete cruise thrust range. At 40% maximum cruise power, the Stage 1 rotor clearance could be brought down to 8 mils with the cooling air set at 100%. Since the objective is an operating clearance no closer than 16 mils, there is an 8-mil design margin. The second stage operating clearance could be brought down to 14 mils at a 40% maximum cruise power setting with the cooling air set at 100%, resulting in a 2-mil design margin.

The maximum clearance without ACC cooling is 6 mils higher on the second stage than on the first stage. This is the result of setting the buildup clearance based on a 25-mil pinch shortly after takeoff. The clearance during takeoff should not be any closer than 25 mils because of the high bending loads, vibration, and ovalization that occur at that condition.

Table 2.4-I. E<sup>3</sup> HP/LP Turbine Maximum Temperature (° F) Gradient Comparison (May 1981 Status).

	40 Seconds into Start RPM, 8420			Maximum Takeoff RPM, 13,287		
	T <sub>Gas</sub>	ΔT <sub>Max. B</sub>	T <sub>Metal Max.</sub>	T <sub>Gas</sub>	ΔT <sub>Max. B</sub>	T <sub>Metal Max.</sub>
HPT						
Vane 1	3631	378	1775	3163	252	1966
Blade 1	2239	268	1514	2560	214	1961
Vane 2	2440	240	1818	2439	179	1960
Blade 2	1647	227	1579	1939	150	1855
LPT						
Vane 1	1474	138	1474	1816	146	1816
Blade 1	1431	---	1431	1668	---	1668

•  $W_f / W_{f, \text{TOTAL}} = 1.0$

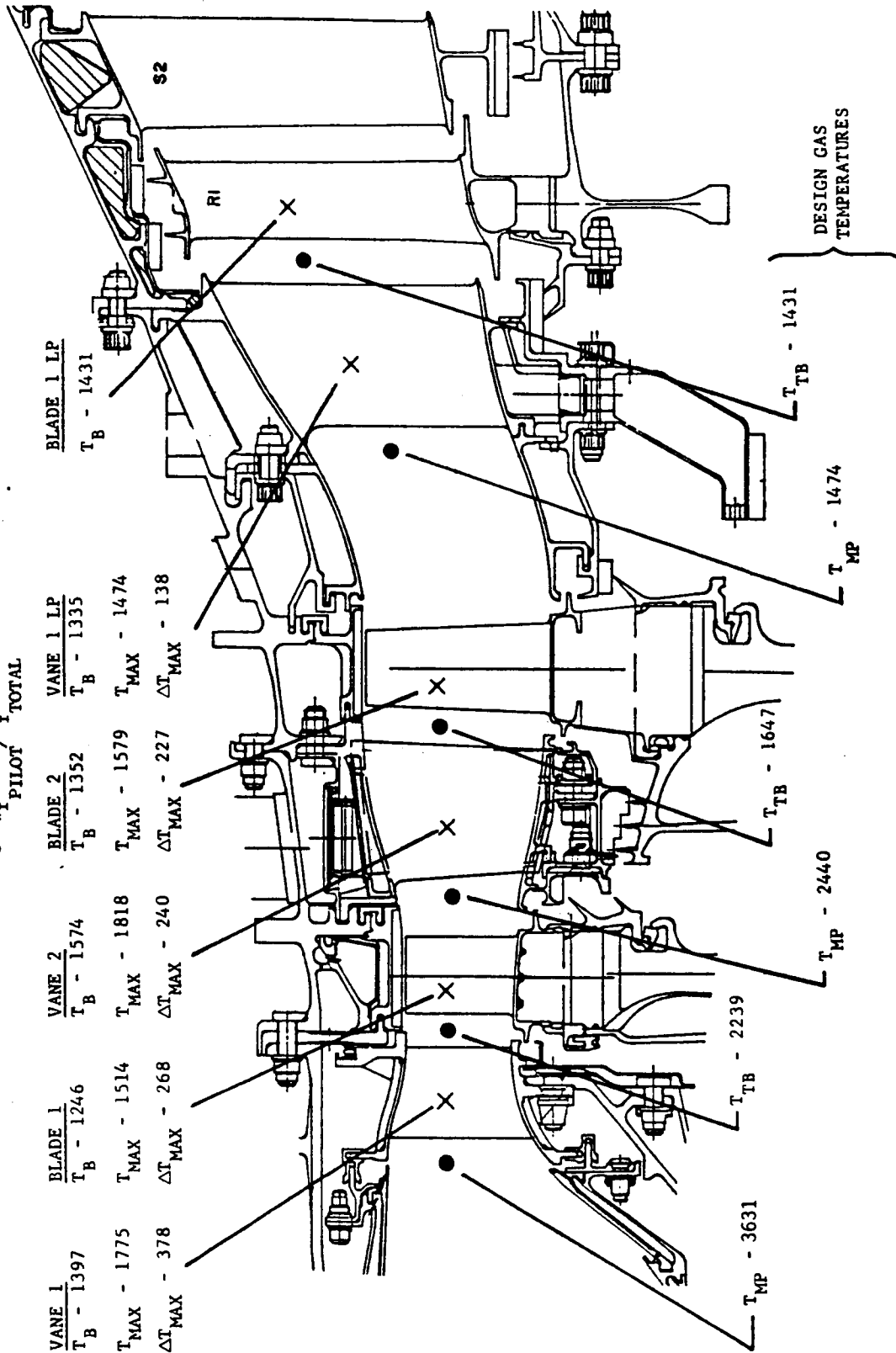


Figure 2.4-7. E<sup>3</sup> HP/LP Turbine Start Temperature (5/81 Status), 40 Seconds into Start.

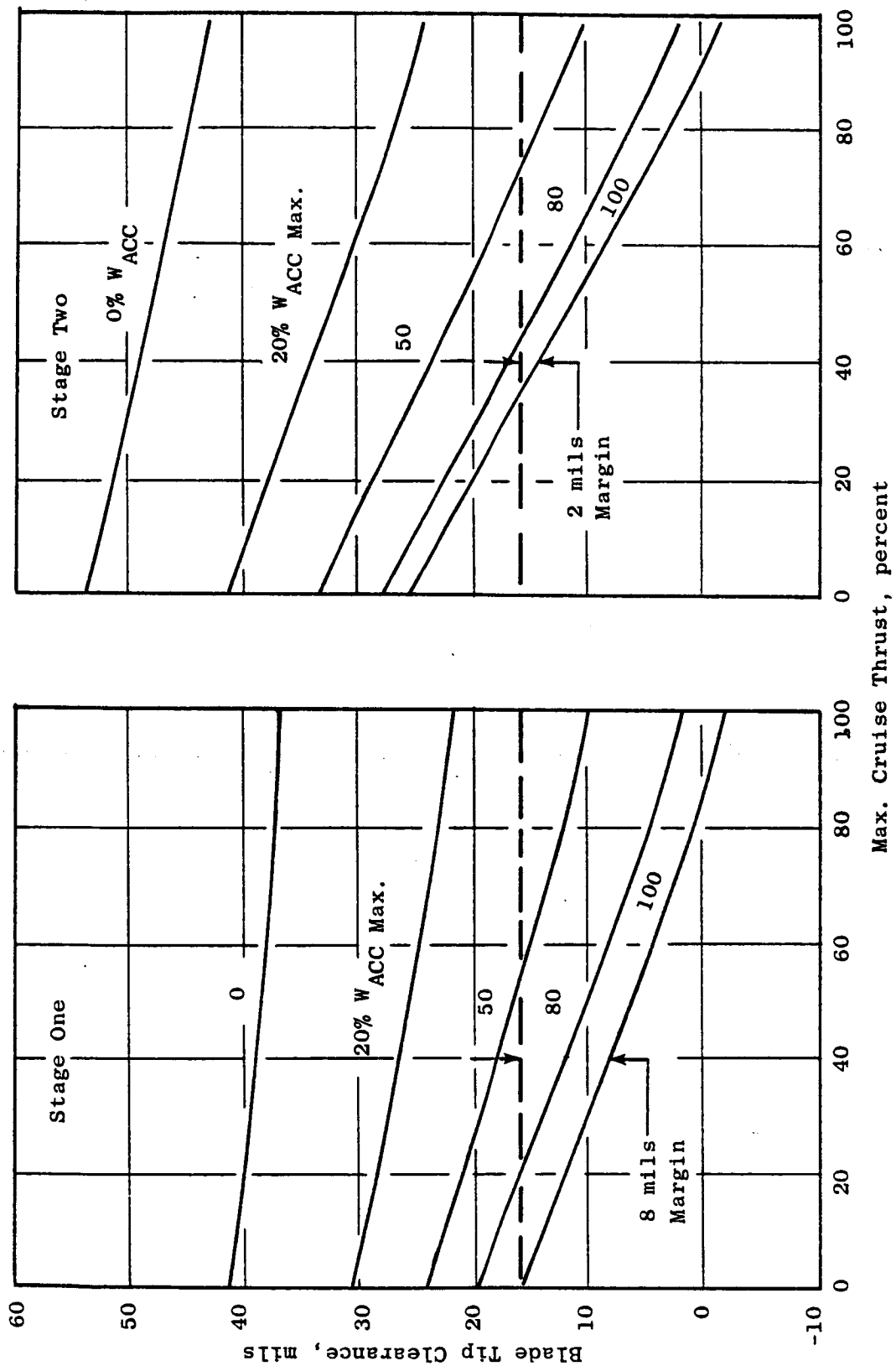


Figure 2.4-8. E<sup>3</sup> HPT Blade Tip Clearance Reduction with Active Clearance Control Cooling at 35 K ft Cruise Thrust.

### Work Planned

Follow engine hardware fabrication for the core and ICLS engines to assure design intent. Define the necessary adjustments to hardware that is not to print and define the necessary adjustments to the cooling supply to maintain safe engine operation.

#### 2.4.3.2 HPT Detailed Mechanical and Technical Progress Summary

##### Nozzles and Structures Design

The Detail Design Report for the nozzles and structures was completed and submitted to NASA for their approval.

The specification document is in the engineering review cycle. This document is in loose-leaf form. Its contents include a general discussion of the material presented to NASA during the detail design review.

All engineering effort under this WBS has been completed. No further reporting will be made under this program.

#### 2.4.3.3 Detailed Mechanical Blades and Rotor Design

##### Technical Progress

The Detail Design Report for the HP blades and rotor structures was completed and submitted to NASA for their approval.

The specification document is in the engineering review cycle. This document contains a brief discussion of the material presented to NASA during the detail design review.

Recent experience with as-HIP René 95 and AF115 powder metal components indicated a reduction in cyclic capability relative to current predicted levels. In order to determine these lower cyclic life levels, fracture mechanics methods were used in analyzing the rotor containing powder metal material.

Fracture mechanics analysis utilized GE-developed statistical techniques. The rotor parts were stress analyzed using the engine conditions expected in the core and ICLS engine tests. This analysis is based on finite-element stresses, volume of material at that stress state, the probability of a defect

within the stress state volume, and the rate of crack propagation (at temperature) from such a defect.

Figure 2.4-9 shows the E<sup>3</sup> HPT rotor cross section with the specific areas and locations analyzed. Surface defects are defined as up to 0.1-inch deep from the surface. The stress and life analyses results are summarized in Table 2.4-II. The 600 cycle was defined as a requirement. This was based on core and ICLS planned testing, conservatively estimated at 300 x 2 (factor of safety) = 600 maximum strain cycles. Based on this number of cycles, the probability of success exceeds 99.9%.

In addition, all components have received high-intensity ultrasonic inspections. This provides added assurance for the projected rotor cyclic life. Any defects detected (see WBS 2.4.8.3) were hand-benched locally; subsequent ultrasonic inspections revealed no further detectable defects.

#### Work Planned

The planned milestones and schedules under this WBS have been completed. No further reporting is planned.

#### 2.4.3.4 Hardware Fabrication and Component Test Support

##### Technical Progress

Major efforts by Engineering to cover manufacture of all turbine components have continued. Through these efforts, improvements in delivery schedules have been obtained. However, additional effort is needed to improve nozzle and blade delivery.

Manufacturing status for HPT components is as follows:

##### Stage 1 Nozzle

All subcomponent parts are available (except inserts). Airfoils are being brazed to the inner and outer bands using two airfoils per band segment.

(See Table 2.4-II)

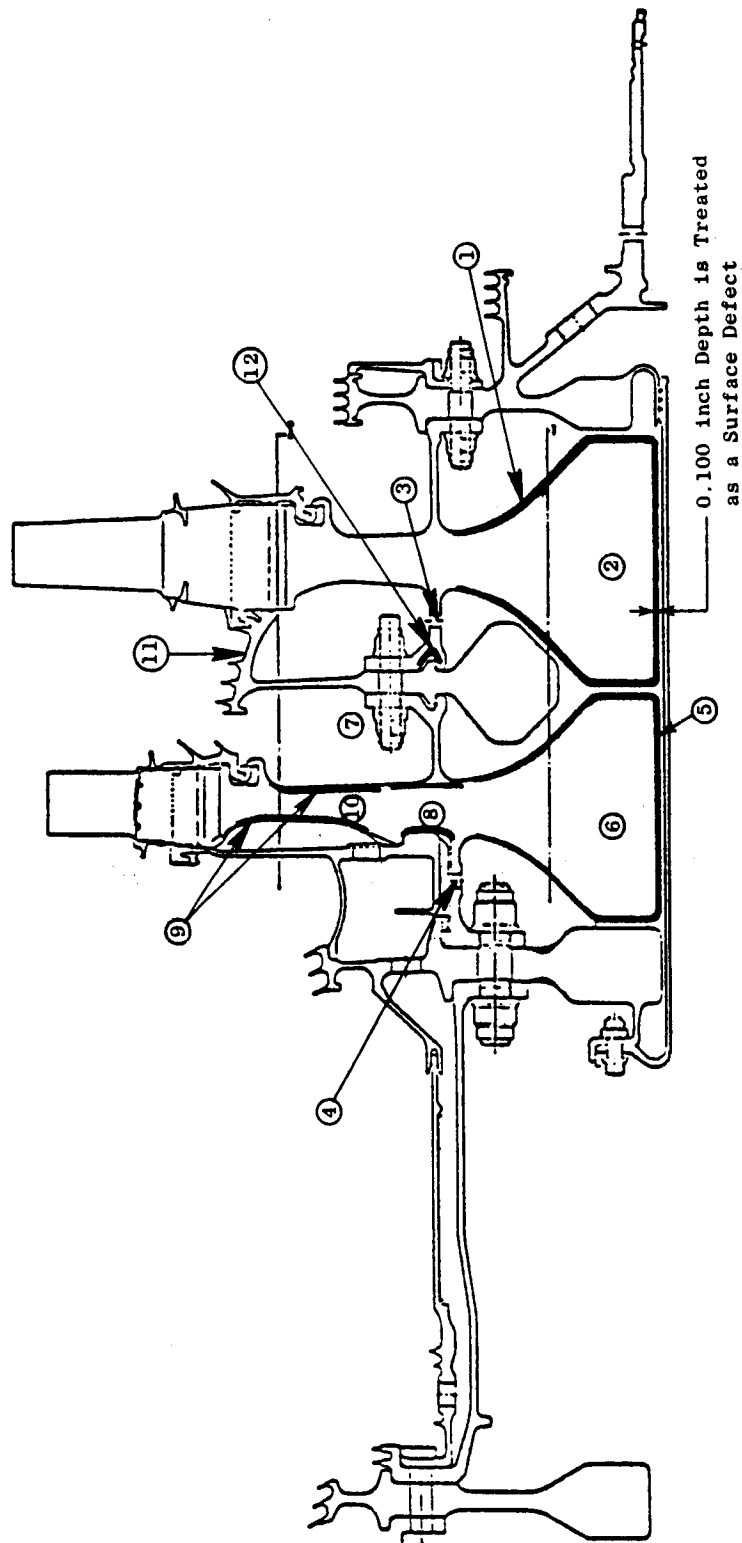


Figure 2.4-9. E<sup>3</sup> HPT Rotor LCF Life Limiting Location.

Table 2.4-II. Reliability of Success for Core and ICLS Engine Test,  
E<sup>3</sup> HPT Rotor.

Location	$\sigma_{\text{Max.}}$ (ksi)	$T_{\text{Max.}}$ (° F)	Cycles	Reliability, percent
1. Stage 2 Disk Bore (Surface)	130	879	600	>99.9
2. Stage 2 Disk Bore (Subsurface)	101	900	600	>99.9
3. Stage 2 Disk Forward Arm Air Hole	146	967	600	>99.9
4. Stage 1 Disk Forward Arm Air Hole	146	937	600	>99.9
5. Stage 1 Disk Bore (Surface)	114	891	600	>99.9
6. Stage 1 Disk Bore (Subsurface)	108	906	600	>99.9
7. Stage 1 Disk Lower Web (Surface)	225	980	600	>99.9
8. Stage 1 Disk Lower Web (Subsurface)	168	980	600	>99.9
9. Stage 1 Disk Upper Web (Surface)	168	1000	600	>99.9
10. Stage 1 Disk Upper Web (Subsurface)	119	1000	600	>99.9
11. Interstage Disk Aft Arm (AF115)	139	1213	600	>99.9
12. Stage 2 Disk Forward Arm Flange	260	710	600	99.9

### Stage 2 Nozzle

Adequate airfoils are available for one set of hardware. The airfoils are presently being assembled into the inner and outer band segments and are being prepared for brazing.

### Stage 1 Blade

Trailing edge core redesign and subsequent rework resulted in improved core yields, thereby increasing the blade casting yields. Presently 81 blade castings are in the machining cycle. Thirteen of these blades will be used for applying instrumentation. Instrumentation application consists of radial grooves in the airfoil and platform for thermocouple application (imbedded in the groove).

### Stage 2 Blade

Core cracking problems associated with the Stage 2 blade during the initial casting evaluation has been resolved. Increase in the radius of the three small holes at the bottom of the turning ribs considerably improved the casting yields.

A total of 22 blade castings are presently being machined. These blades will be used for instrumentation application. An additional 82 blades are being processed through the final casting inspection.

### Stage 1 Ceramic Shrouds

Thirty-five ceramic shroud castings are being processed in the manufacturing cycle. Twenty-eight shrouds have been sprayed with zirconia, while seven shrouds have been machined and modified for the solid shroud design.

### Stage 2 Solid Shrouds

Twenty-nine shroud castings are presently being machined. The NiCrAlY spray coat has been completed and dimensionally ground to the required radius.

#### Work Planned

- Continue to maintain manufacturing support.
- Establish and determine ways to improve delivery dates.
- Continue to review any dimensional discrepancies and establish procedures to rework part if necessary.

#### 2.4.3.5 HPT Core/ICLS Support

##### Technical Progress

All drawings showing location and component rework for instrumentation applications have been issued. Except for insert rework (Stage 1 and 2) to channel instrumentation leads, all rework will have been completed by September 30, 1981.

#### Work Planned

- Complete instrumentation rework or inserts.
- Support Evaluation and Instrumentation in location and tack welding instrumentation leads.
- Complete analysis for defining borescope limits for blades in core and ICLS testing.
- Continue core buildup support.

#### 2.4.4 HPT Mechanical Design Testing

##### Technical Progress

Drawings defining the blade mounting fixtures for high cycle fatigue tests were issued.

A test program plan defining the type of static testing to determine the relative vibratory blade stress distributions and natural frequencies was issued to the applied mechanics lab.

Rotating cylindrical structures (shaft, inner and outer liners) are being prepared for static vibratory frequency determination. Values are to be compared with analytical results and evaluated relative to engine operating speeds.

Work Planned

- Complete blade stress frequency distribution determination.
- Complete rotating structures vibratory frequencies evaluation.
- Continue and coordinate the hot high cycle fatigue tests for blades in Stages 1 and 2.
- Initiate blade damping tests.

2.4.5 High Pressure Turbine Cooling Development Testing

Technical Progress

Due to the critical nature of the HPT and LPT active clearance control (ACC) system, it is essential that its operation be completely understood before engine test if the total system performance potential is to be realized. The ACC system for both the HPT and LPT consists of a scoop to recover fan discharge air, a control device to schedule the correct amount of air, and a distribution system to cool the exterior of the respective turbine casings. Spent air, after impinging on the casing, is routed through the LPT aft frame and tail cone to the stinger where it is ejected out the back with sump purge air and compressor purge air.

Between the fan discharge and stinger, not one pressure loss is dominant, so no single pressure loss can be considered to be insignificant. Concurrently, there is not a large overall pressure drop in the system. For these reasons, it is essential that the control air be extracted as efficiently as possible from the fan discharge duct and that flow characteristics over the operating range be well documented. The current ACC system calls for a high-performance scoop installed in the side of the pylon skirt. This scoop (Figure 2.4-10) will be split into two equal parts to separate the HPT and LPT ACC systems, and prevent interaction between the two circuits.

The model test of the scoops, which was carried out in a small wind tunnel at one-half scale, had three objectives. Of primary importance was the procurement of detailed data on the recovered pressure that would be available for use in the ACC system. This information is essential for proper scheduling of clearance control valving mechanisms at various combinations of air scoop

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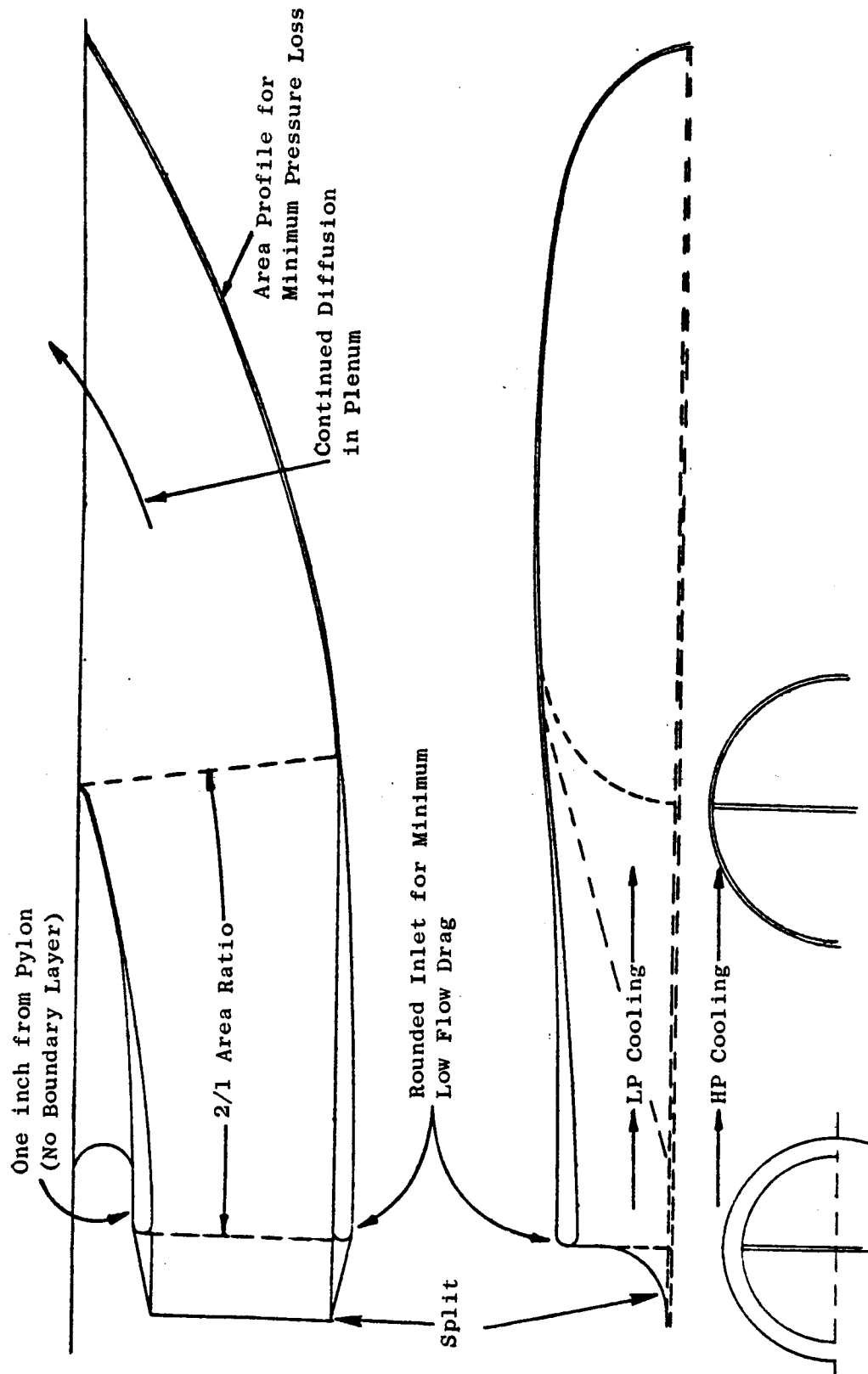


Figure 2.4-10. HP/LP ACC Scoop Features.

flows and fan discharge duct Mach numbers. Of equal significance was the verification of any interaction between the LPT and HPT scoop recovery systems. Secondary to the former was an attempt to experimentally verify prior analytic predictions to the aerodynamic drag penalty associated with the scoop being located in the fan discharge duct.

During this reporting period, final installation of the air scoop and duct assembly, testing, and the reduction of the pressure recovery data were accomplished. Thirty-seven test points were recorded over a range of duct Mach numbers (from 0.20 to 0.55) representing conditions seen by the full-scale scoop in the fan duct. Flow extraction ranged from zero to over 0.122 lb/sec per duct side simulating the required ACC system flow requirements, maximum to minimum controlled clearance respectively. Recovery plenum pressures and scoop inlet plane total and static pressures were recorded at each test point. Additionally, total pressure traverses were made in both axes, perpendicular to duct flow upstream and downstream of the scoop, in order to define the scoop aerodynamic drag loss at each Mach number tested. A schematic view of the scoop test is provided in Figure 2.4-11.

Results of the pressure recovery test are presented in Figure 2.4-12 where the percentage of dynamic head recovered is plotted against the area normalized flow function ratio. As shown in the figure, the percentage of recovered head ranges from a high of 95% to 100% at lowest flow situations (ACC-off) to a low of 75% to 80% at the maximum flow condition (ACC-min. clearance). Preliminary design goals called for a recovery of at least 50% of the fan duct dynamic head. Data results indicate that more than adequate pressure will be available for satisfactory clearance control system operation.

#### Work Planned

- Complete film cascade data analysis and report.
- Complete ACC scoop report.
- Complete vane trailing edge slot heat transfer report.

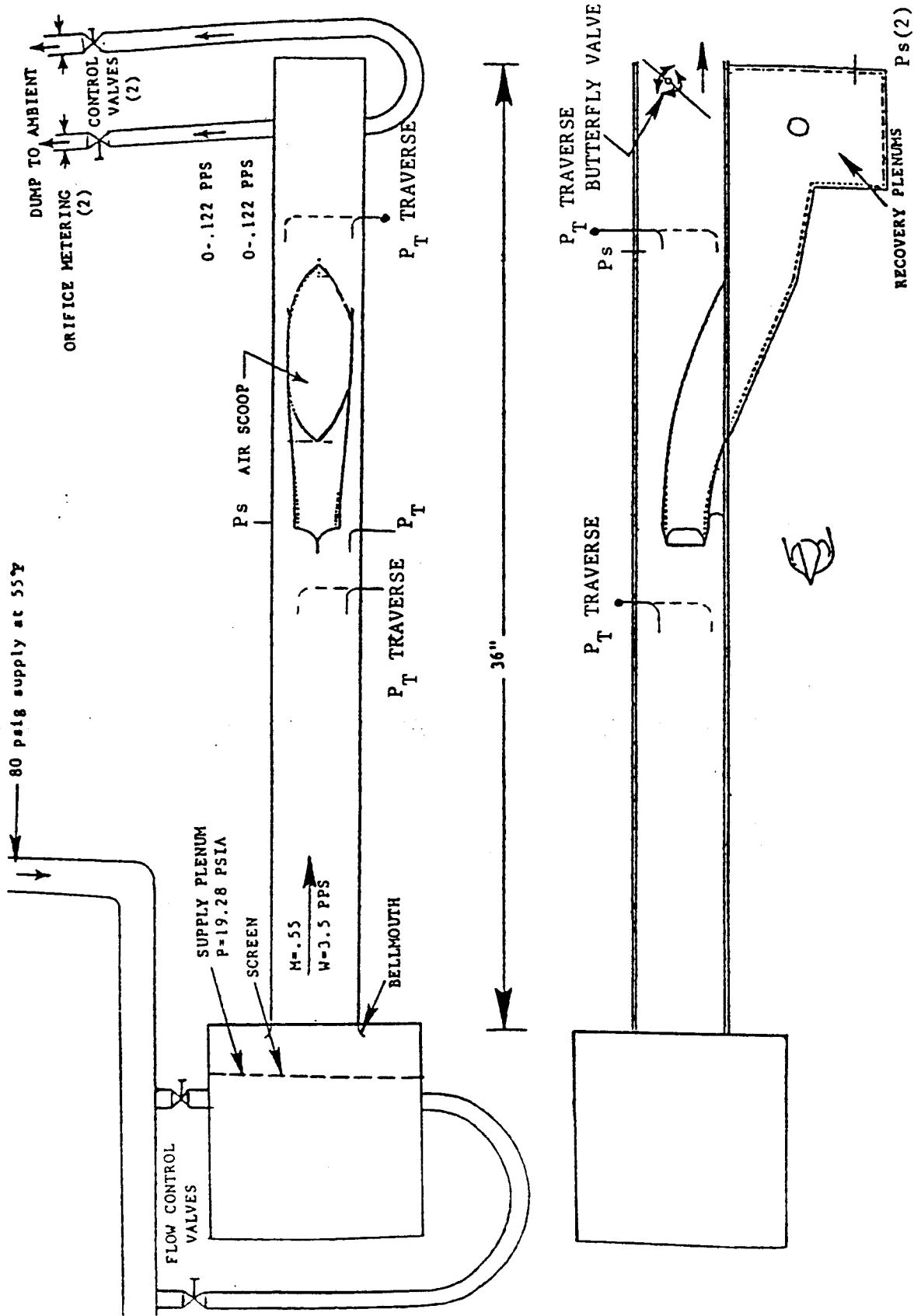


Figure 2.4-11. HP/LP ACC Scoop Model Test Airflow Schematic at Design Point.

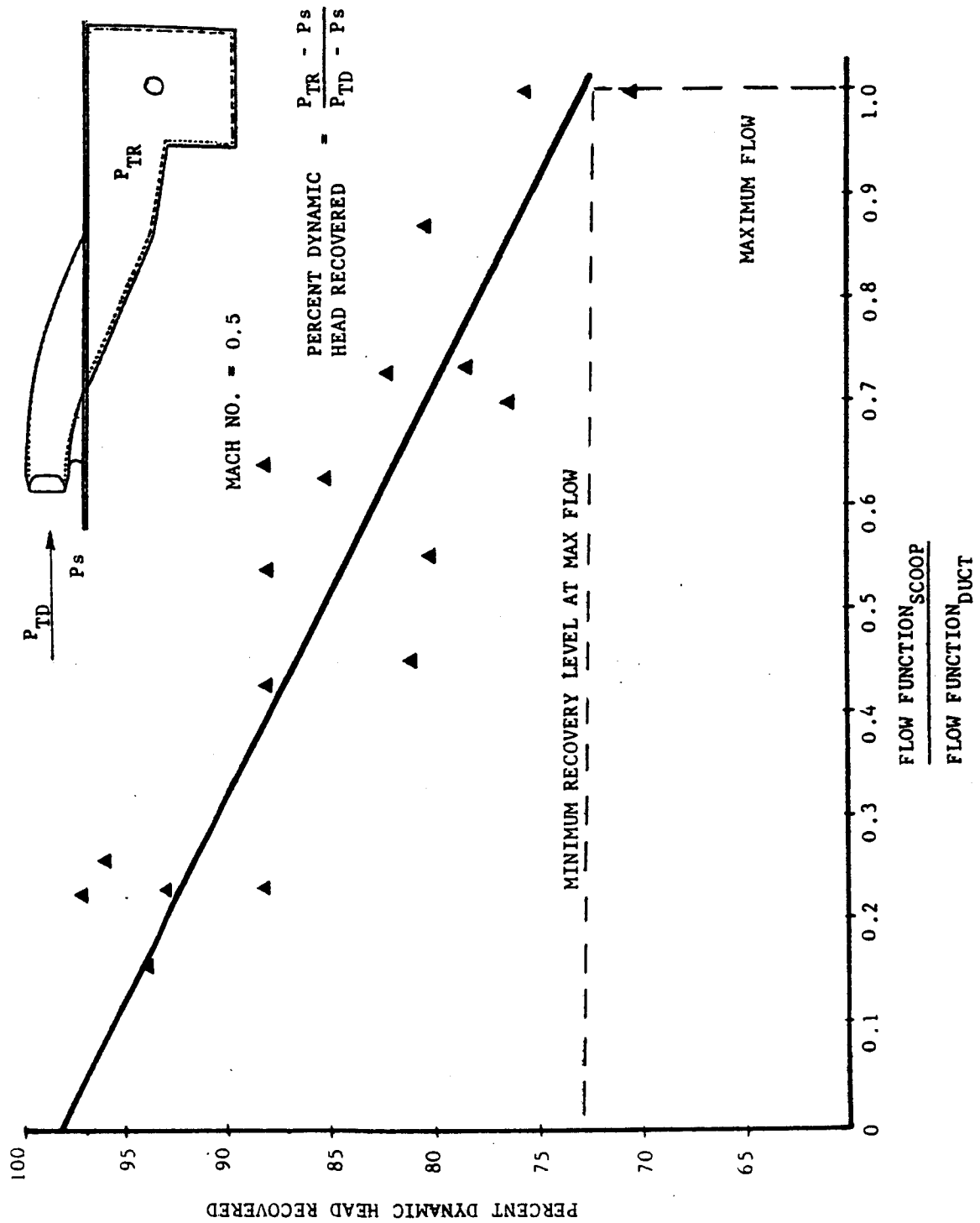


Figure 2.4-12. HPT/LPT ACC Scoop Model Test Pressure Recovery Performance.

#### 2.4.7.1.1 Ceramic Shroud Process

##### Technical Progress

A  $\text{ZrO}_2$ -8 wt%  $\text{Y}_2\text{O}_3$  powder source was selected based on sprayability of powder and comparative thermal shock testing. Metco was identified as the powder source.

Plasma spray coating parameters for the superpeg ceramic shrouds were identified. Based on microstructural and macrostructural analyses, the shrouds will be automatically sprayed using the rotating drum method. Application of a stop-off material to the peg tips and periodic removal of coating from the peg tips has greatly minimized the circumferential voiding of the coating at the peg tips.

Development of a coating NDE procedure is in progress. Initial analyses of ceramic coated panels containing known defects led to the selection of an infrared method. This method showed sensitivity to known defects and could be readily adapted to evaluate ceramic shrouds. Three CF6-50 superpeg shrouds were fabricated for NDE inspection and thermal shock testing. Following their fabrication and prior to Lynn thermal shock testing, each shroud was isothermally cycled to generate coating flaws. After thermal shock testing, each shroud was sectioned in areas indicated by infrared analysis and shown to contain delaminations. Microstructural analysis of the coating revealed no evidence of coating delamination or separation. Infrared indications were attributed to (1) areas of thin  $\text{ZrO}_2$  coating, or (2) areas of Hastelloy X superpeg insert delamination (due to poor braze joints).

Two  $\text{ZrO}_2$  coated E<sup>3</sup> superpeg shroud castings (no Hastelloy X insert) were also thermal cycled to produce delaminations. After 40 furnace cycles, one shroud contained defect indications. This shroud is under microstructural investigation to determine the source of the indications.

##### Work Planned

Complete development of the infrared NDE procedure.

#### 2.4.7.1.2 Component Test of Ceramic Shrouds

##### Technical Progress

The manufacture of the test fixtures for thermal cycle proof test of the Stage 1 ceramic shroud configuration continued. The expected completion date is October 1981.

An Engineering review of test measurement parameters relative to temperatures and procedures has been finalized.

The shrouds to be used for this test have been surface sprayed, coated, and are now undergoing flowpath grinding operation.

##### Work Planned

- Complete the thermal cycle proof test of ceramic shrouds and evaluate the results relative to engine testing.

#### 2.4.7.2.1 Thermal Barrier Processes

##### Technical Progress

The objective of this program is to develop a thermal barrier coating (TBC) system and demonstrate its adequacy for the energy efficient engine. Previous reports have described the progress of earlier tasks that led to the selection of a coating system, the development of processes for applying the coating to engine components, qualification of the coating through mechanical property tests, component fatigue tests, a rig test, and application of the coating on components for factory engine testing. A factory engine test was run in which there were several TBCd CF6-50 Stage 2 blades. The test were terminated after 626 "C" cycles due to turbine FOD unrelated to the coated blades. The Stage 2 blades and coatings were extensively damaged as reported earlier.

##### Engine Test

During this report period, several TBCd HPT blades and vanes were run for 1000 "C" cycles in another CF6-50 factory engine test. The coating of these components - Stage 1 and 2 vanes, and Stage 2 blades - was described in the

previous semiannual report. The four Stage 1 vane pairs and seven Stage 2 vane pairs were coated in selected areas of the airfoils and bands with 0.005 in. of NiCrAlY bond coat and 0.012 in. of  $ZrO_2$ -20% $Y_2O_3$  top coat.

The 10 Stage 2 blades tested were coated with nominal thicknesses of 0.005 in. NiCrAlY bond coat and 0.010 in.  $ZrO_2$ - $Y_2O_3$  topcoat. Five of the blades had a topcoat of  $ZrO_2$ -20% $Y_2O_3$ , and five had a topcoat of  $ZrO_2$ -8% $Y_2O_3$ . Of the blades with  $ZrO_2$ -8% $Y_2O_3$ , two were coated as part of this program and three were coated at GE-CRD under Contract NAS3-21727. The coating applied at GE-CRD was made from zirconia spray powder from a different vendor (Zircoa Corning) from that used at GE-AEG (Metco). There were several other material and coating process variables which differentiate the coatings applied at these two sites.

#### Blades

Some minor coating damage consisting of small chips from the edge of the coating at the tip of the blades occurred during tip grinding of the blades during engine assembly. The next examination of the blades took place after 27 hours of engine checkout. Borescope examination revealed some coating damage of the leading edge near the tips of the TBCd blades (Figure 2.4-13). Some of the ceramic layer was missing, but it was not apparent through the borescope whether the loss occurred as a result of thermal cycling or impact damage. Borescope inspections after 225, 450, and 663 cycles of testing showed the damage still to be limited to the area from about 75% span to the tip, but the damage appeared to progress somewhat during the course of the testing.

At the conclusion of the 1000 "C" cycle test, the Stage 2 blades and vanes were removed from the engine and examined. Visual examination of the TBCd blades showed the TBC to be in excellent condition, except at the leading edge on the suction side (Figure 2.4-14). There was no loss of coating on the platforms except for one spalled area on one blade. And there was no loss of coating from the pressure side of the airfoils or from the greater part of the suction side of the airfoils.

All the blades had a similar pattern of coating damage at the leading edges, although the extent of damage varied from blade to blade. In small

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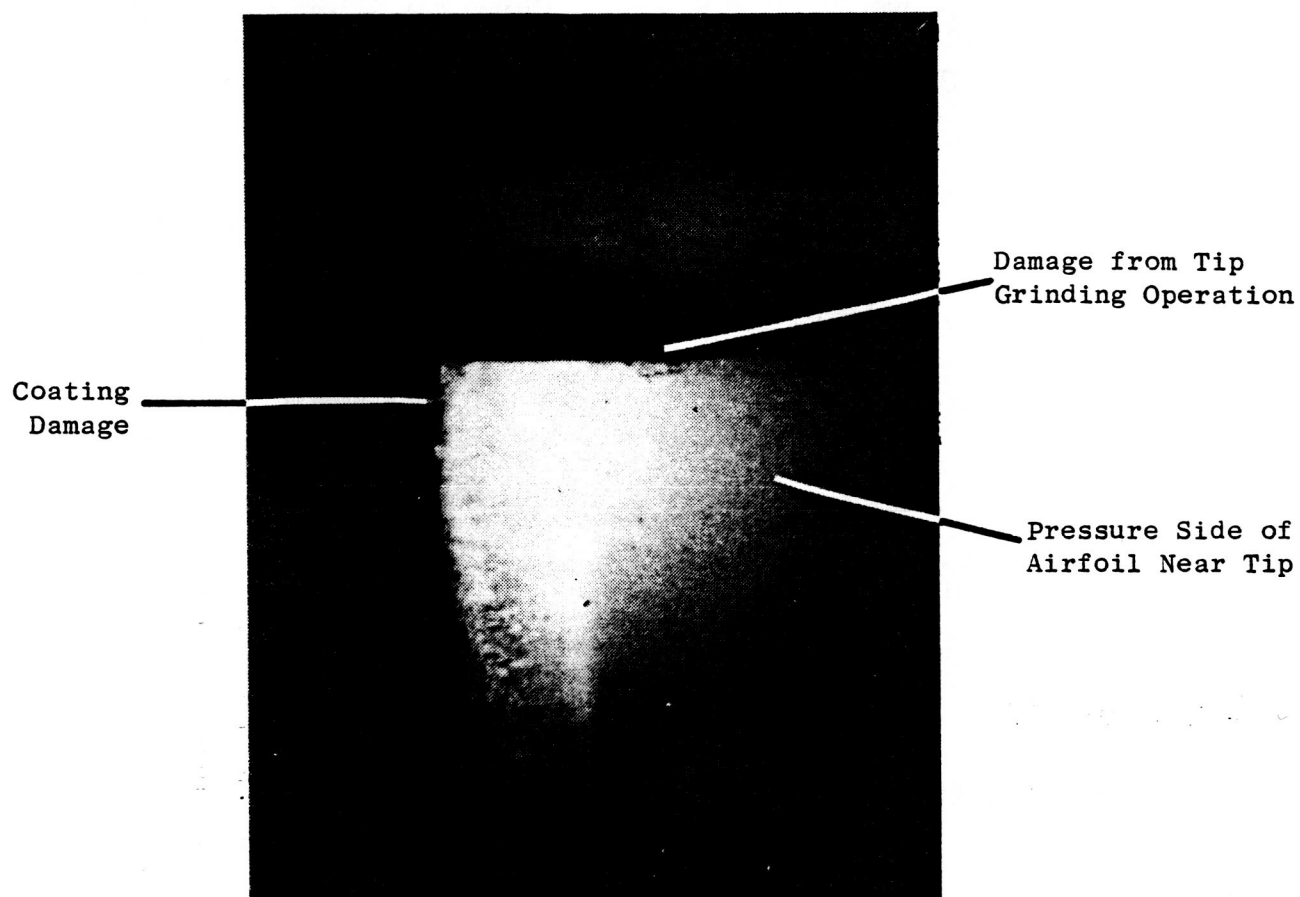
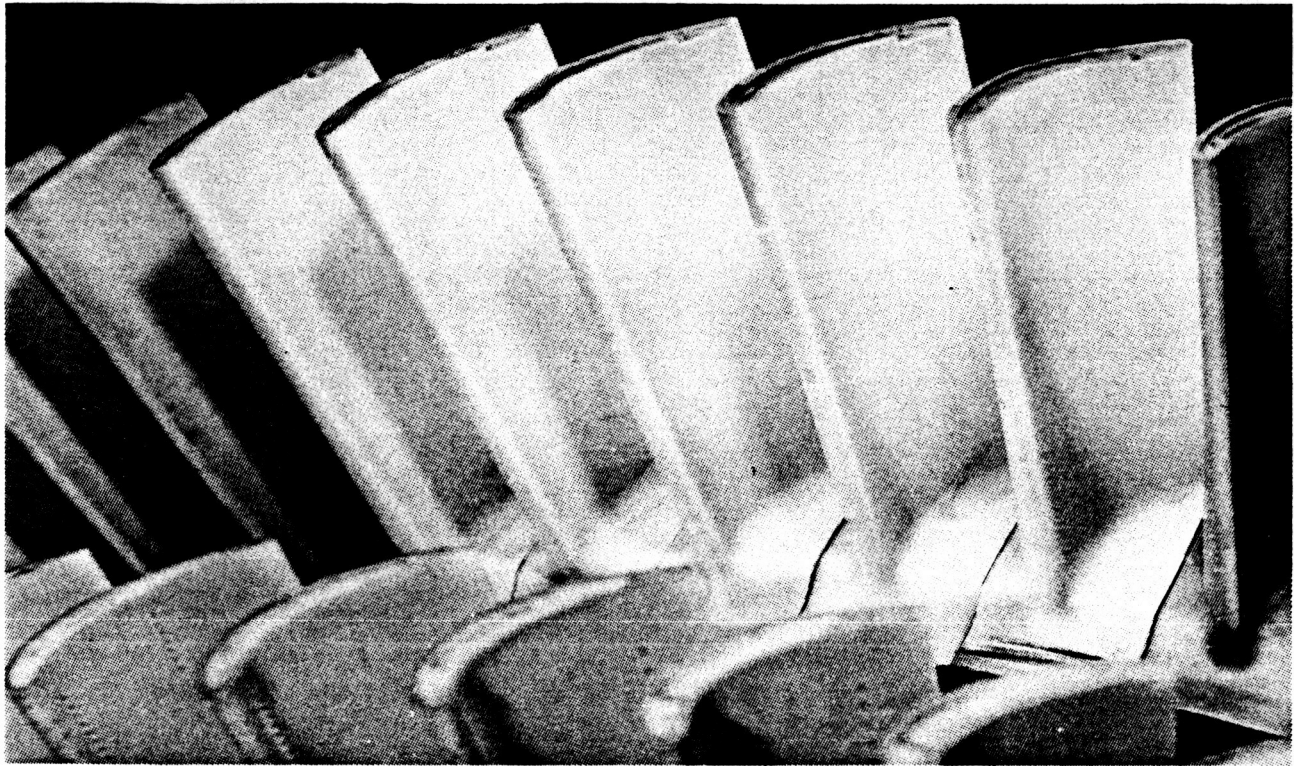


Figure 2.4-13. Photograph Through Borescope of Coating Damage After 27 hours of Engine Check-Out. (Blade A2139).

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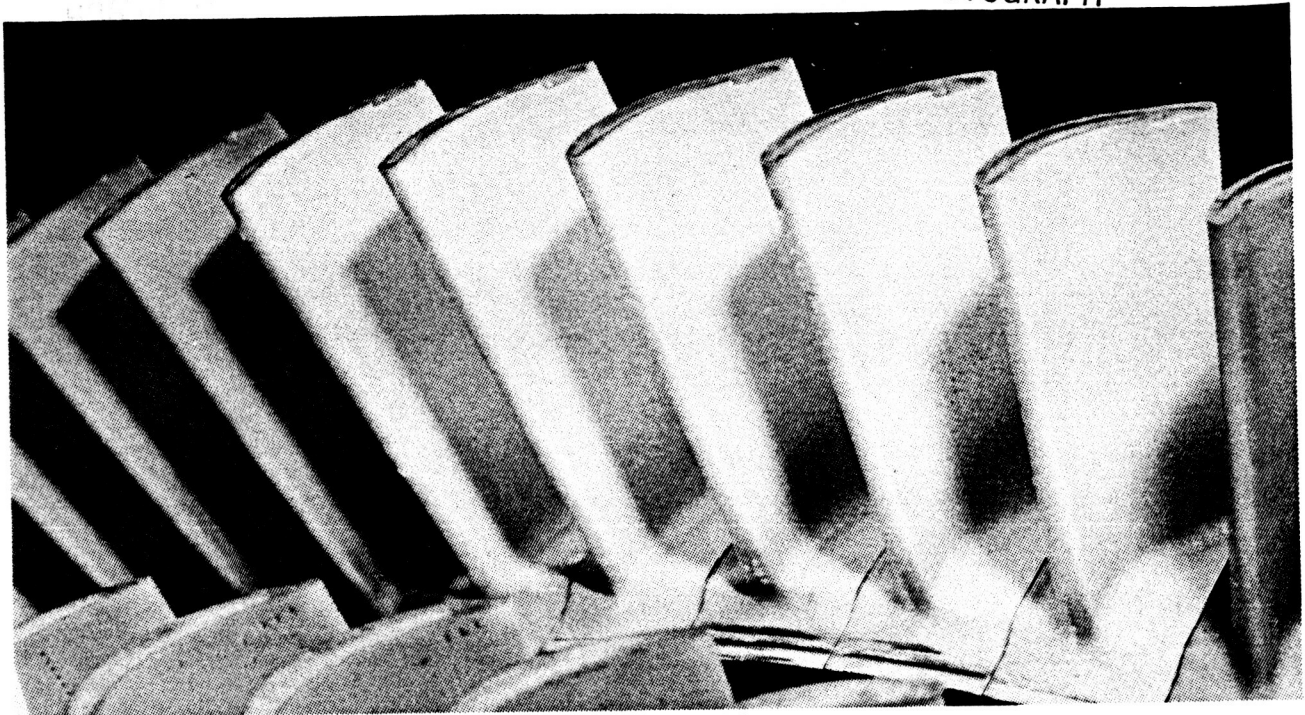
Pressure Side



Leading Edge

Figure 2.4-14. Thermal Barrier Coated Stage 2 Blades After 1000 "C" Cycle Engine Test.

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Pressure Side



Leading Edge

Figure 2.4-14. Thermal Barrier Coated Stage 2 Blades After 1000 "C" Cycle Engine Test (Concluded).

areas of the leading edge at the blade tip (ranging in size from 0.03 in.<sup>2</sup> to 0.16 in.<sup>2</sup> and averaging 0.1 in.<sup>2</sup>) the entire thickness of the ceramic layer was lost. The loss of ceramic layer in these areas may be related to a number of factors: development of cracks in the ceramic layer during tip grinding, spallation of the ceramic layer due to thermal cycling and geometry effects, and impact and erosion damage.

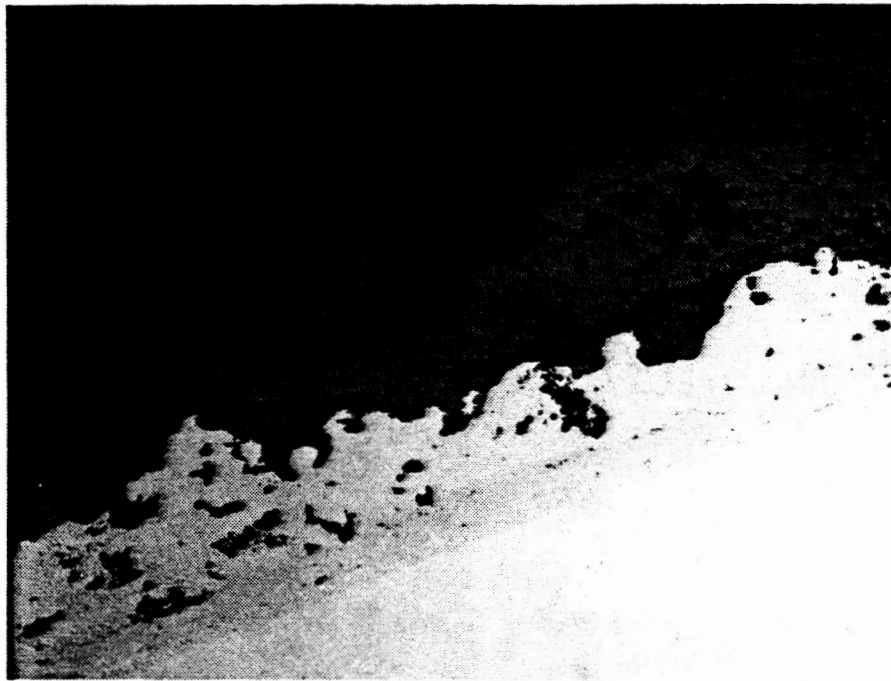
In other areas of the leading edge, damage was characterized by a roughened coating surface, the presence of pockmarks and small craters, and isolated loss of ceramic coating. In these areas a thin layer of the ceramic coating was still present. This damage appeared to be the result of particulate impingement. Blades without a TBC (Codep only) also showed signs of particulate impingement at the leading edge. This area appeared rougher than the rest of the airfoil and showed some foreign material adhered to the surface at the leading edge. Identification and source of this material is under investigation.

Three TBCd blades with each type of ceramic layer composition and one uncoated (Codep only) blade were sectioned at 40%, 70%, and 90% span and in the platform region for metallographic examination. Microstructural examination showed the TBCs on all three blades to be in excellent condition in all areas except at the suction-side leading edge where the ceramic layer had been damaged.

Figure 2.4-15 shows a typical microstructure of the coating at the leading edge where the ceramic layer had been lost during engine test. It can be observed that the bond coat and the adjacent ceramic layer are still in good condition. Figure 2.4-16 shows a typical microstructure of the coating on the rest of the airfoil surface away from the damaged region. The coating appears to be in excellent condition and shows no evidence of cracking, separation, or erosion/impact damage. There was essentially no difference in the condition of the bond coats and ceramic topcoats on the blades with different ceramic layer compositions of 8% and 20% Y<sub>2</sub>O<sub>3</sub> stabilized zirconia.

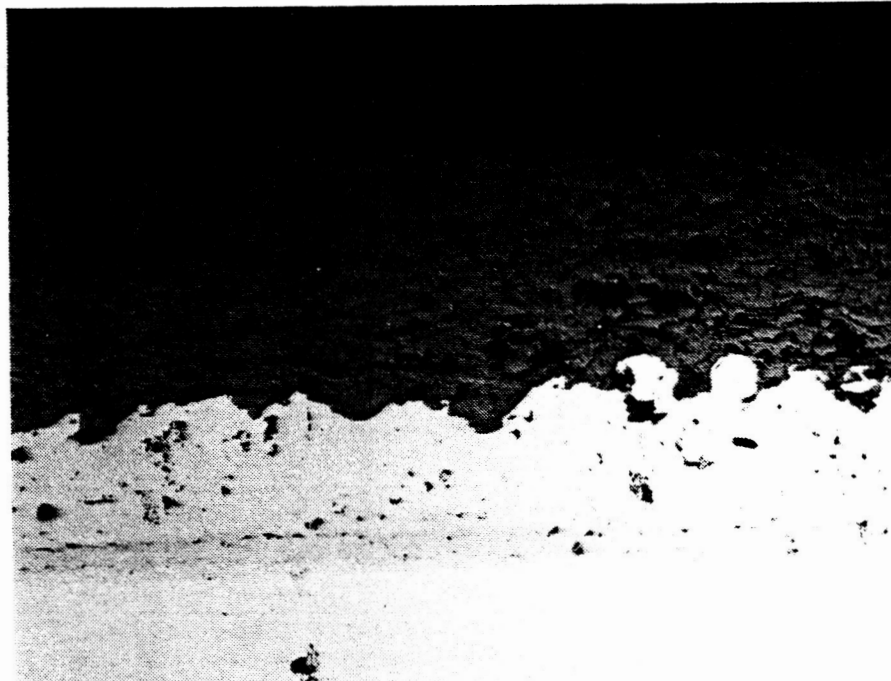
Microscope examination of the sectioned blades showed the bond coat to be intimately bonded to the Codep layer on the blades. The bond coat was uniform in thickness, highly dense in most areas, and its microstructure was typical

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Bond Coat: Ni-22Cr-10Al-1Y; Top Coat:  $\text{ZrO}_2$ -20%  $\text{Y}_2\text{O}_3$  (100x)

Figure 2.4-15. Microstructure of Engine Tested (1000 "C" Cycles)  
Stage 2 Blade on the Suction Side Near the Leading  
Edge at 90% Span.



Bond Coat: Ni-22Cr-10Al-1Y; Top Coat:  $\text{ZrO}_2$ -20%  $\text{Y}_2\text{O}_3$  (100x)

Figure 2.4-16. Microstructure of Engine Tested (1000 "C" Cycles)  
Stage 2 Blade on the Suction Side Away from the  
Leading Edge at 90% Span.

of low-pressure plasma-sprayed bond coats. It was observed that some interdiffusion between the Codep layer and bond coat, and the Codep layer and blade material (René 80) had taken place during the engine test; however, oxidation of the bond coat was minimal. Formation of an oxide layer at the top-coat/bond coat interface, such as had been observed in laboratory thermal exposure testing, was not apparent. This is probably due to the relatively short time (~277 hours) and the relatively low temperature (~1800° F) experienced during engine testing of the bond coat of the Stage 2 blades. Further analysis by electron microprobe (EMP) is underway.

X-ray diffraction analysis was performed on ceramic layer samples taken from three blades in order to observe any phase changes that had taken place during engine test. The results showed the  $\text{ZrO}_2$ -20% $\text{Y}_2\text{O}_3$  coating to be mostly cubic phase, with a small percentage of monoclinic phase, whereas the  $\text{ZrO}_2$ -8% $\text{Y}_2\text{O}_3$  coating consisted of a mixture of cubic/tetragonal phases with a small percentage of the monoclinic phase. Presence of a small amount of the monoclinic phase in the  $\text{ZrO}_2$ -20% $\text{Y}_2\text{O}_3$  coating indicates that some phase transformation had taken place during the engine test. This is consistent with observations from the previous engine test and laboratory cyclic thermal exposure testing. There was essentially no change in the phase composition of the  $\text{ZrO}_2$ -8% $\text{Y}_2\text{O}_3$  coating during the engine test.

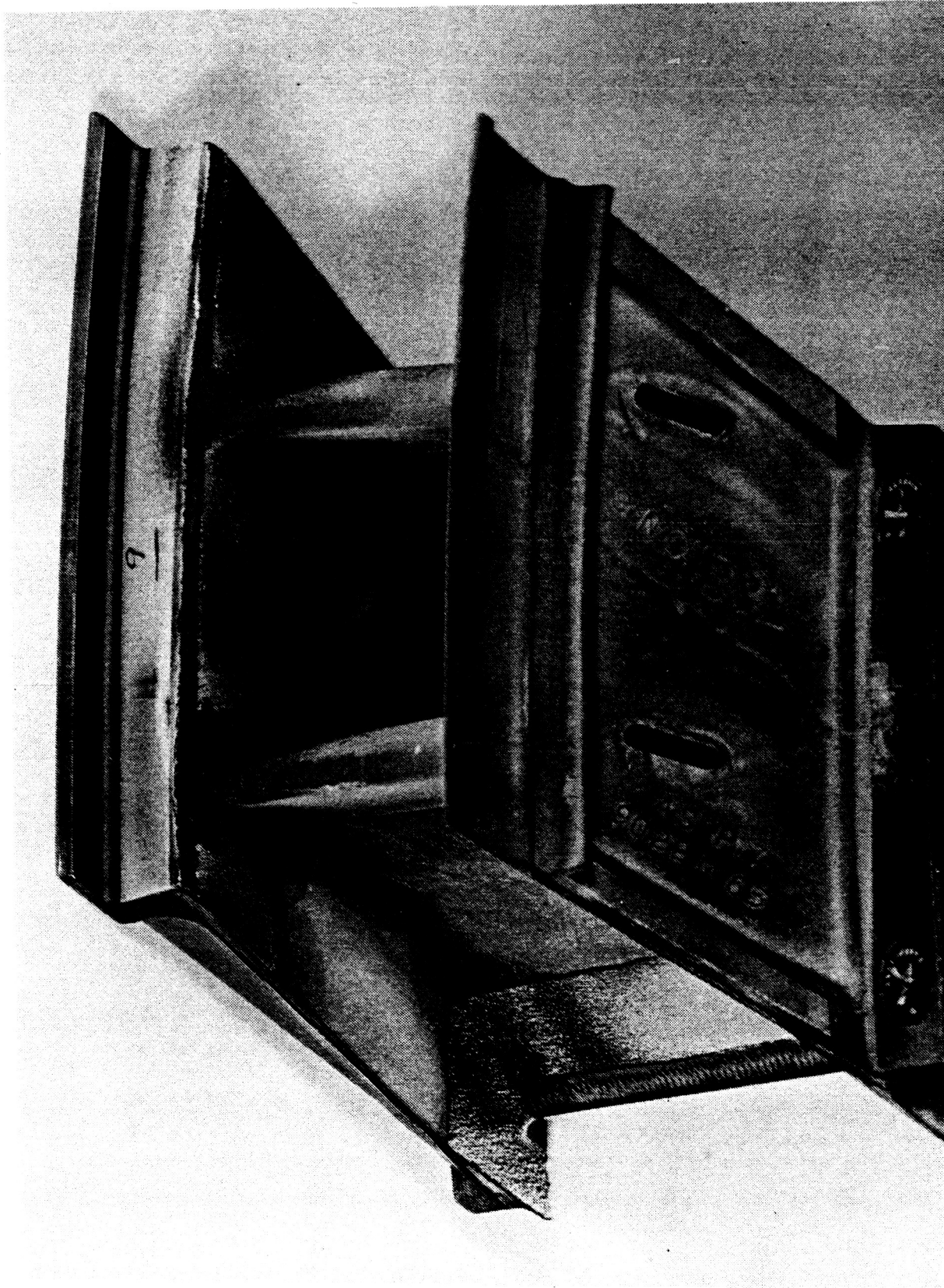
Surface roughness of the engine-tested TBCd blades was similar to that of untested blades, except on leading edges where impact damage had occurred.

Overall, the TBC performed well on the Stage 2 blades. Most of the damage to the coating appears to have been caused by particle impingement rather than by thermal cycling, except for the region of the leading edge near the tip of the blades.

#### Vanes

Visual examination of the engine-tested TBCd Stage 2 vanes (Figure 2.4-17) showed that the TBC was damaged fairly extensively on the outer one-third to two-thirds of the airfoil leading edges. Some pretest damage occurred during shroud grinding. Erosion of the TBC was rather severe at the forward edge of

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Bond Coat: Ni-22Cr-10Al-1Y Top Coat:  $\text{ZrO}_2$ -20%  $\text{Y}_2\text{O}_3$   
Figure 2.4-17. Photograph Showing the Typical Damage to the TBC on Engine Tested  
Stage 2 Vane.

the outer bands and adjacent to the outer bands on the convex side of the airfoils just aft of the leading edge; local penetration of the TBC occurred on about one-fourth of the TBC airfoils. The coating patches were in good condition on the airfoil trailing edges and on the aft edges of the inner/outer bands, although some appeared to be quite thin. A more detailed metallographic analysis is currently underway.

Engine-tested TBCd Stage 1 vanes are not yet available for examination.

#### Work Planned

Complete the evaluation of the engine-tested TBCd high pressure turbine components.

#### 2.4.7.2.4 CF6-50 Thermal Barrier Coating Heat Transfer Evaluation

The purpose of this program is to supply heat transfer support to the development of a zirconia coating for the turbine flowpath components. As the first phase of that development, the zirconia was evaluated in the CF6-50 engine.

The zirconia was evaluated as local patches on the Stage 2 vane and as a complete coating on the Stage 2 Blade. The engine was cycled through 1000 "C" cycles which encompasses an accel from ground idle to maximum takeoff, decel to flight idle before undergoing a quick accel to thrust reverse power and decel back to ground idle. Each "C" cycle takes approximately 5 minutes and subjects the hardware to an equivalent of one flight mission per cycle.

The results of the test were very encouraging. No spalling was observed except at a few small places near the blade squealer tip. Some FOD damage to the suction gill area of the blade TBC coating above the 50% span was observed but may have been the result of the loss of some of the shroud filler material from the first stage. This is a characteristic of the CF6-50 engine which has been eliminated on the CF6-80 and E<sup>3</sup>.

The stage two vane hardware also looks good except at the leading edge where some coating damage was observed.

Work Planned

None - Work Completed.

2.4.7.3 Alloy Mechanical Behavior

Technical Progress

Successful application of directional alloys to aircraft engine turbine blades and vanes requires careful definition and evaluation of the mechanical behavior of these materials in order to capitalize on their high strength potential and at the same time avoid failures in new modes or weaker off-axis directions. Present effort is aimed at developing and applying understanding of the behavior of the candidate directional materials DS René 150 and MA754 so that they may be successfully applied in blades and vanes of the E<sup>3</sup>.

As described in previous semiannual reports, two major areas of activity are being addressed: (1) thin wall creep rupture of DS René 150 and (2) low cycle and thermal fatigue of DS René 150 and MA754 under conditions relevant to blade and vane fatigue cracking.

Progress in these areas in the past 6 months is described below:

- Thin Wall Creep and Rupture of DS René 150

Work on this portion of the program has been completed and was reported in the last 6-month progress report.

- Complex Fatigue Effects

No further effort is planned in this activity.

Work Planned

This program has been down-scoped and no further activity is planned.

2.4.8.1 Stage 1 Blade Manufacturing

Technical Progress

The Stage 1 blade core redesign at the trailing edge slot locations and the subsequent core rework were successful and resulted in higher core yield.

The original core configuration, based on the blade design cooling hole pattern feeding air to the trailing edge, had a high rate of rejects due to cracks originating in the cooling feed holes. Adequate cores are now available to complete the quantity of castings on order.

A total of 81 blades are presently in the machining operation. Thirteen of these blades are planned for instrumentation for the core engine test. These blades contain radial grooves for embedded thermocouple applications. Strain gages will be surface mounted.

As part of the quality control inspection of the braze joint for the tip cap and core plug, an inspection process was necessary to assure bonding integrity. This procedure was successfully established using X-ray blade angle views.

Delivery for the balance of blade castings to GE for the tip cap brazing operation will be completed in October 1981.

Replanned manufacturing costs for Blade 1 were completed; production costs are now within planned funding.

#### Work Planned

- Complete the machining of the first set of Stage 1 blades (including application of physical vapor deposition environmental coating (PVD) for noninstrumented blades)
- Initiate blade machining for the second set of hardware
- Continue close coordination with the casting and machining vendor during the blade manufacturing processes for the balance of the order
- Interface with instrumentation personnel in approving the blade instrumentation drawing.

#### 2.4.8.2 Stage 2 Blade Manufacturing

##### Technical Progress

A total of four separate casting lots have been processed through all the brazing and casting operations. The resulting yield from these lots is 90

blades, which have been supplied to the machining vendor. Eighteen of these blades are being processed for instrumentation application.

A quality control inspection of the tip cap braze was established for the Stage 2 blade. The procedure is similar to the process established for the Stage 1 blade tip cap braze joint.

Delivery for the balance of blade castings on order for the tip cap brazing to be performed through GE will be completed by October 1981.

#### Work Planned

- Complete machining of the first set of Stage 2 blades (including application of PVD for noninstrumented blades)
- Initiate blade machining for second set of hardware
- Continue close coordination with the casting and machining vendors during the blade manufacturing process for the balance of the order
- Interface with instrumentation personnel in approving the blade instrumentation drawing.

#### 2.4.8.3 Stage 1 and 2 Disk Manufacturing

##### Technical Progress

Stage 1 and 2 disk machining has been completed and accepted by Engineering. During this 6-month period the disks were processed through the form cutting of the disk posts, all final machining, EDM of grooves, shot peening, and final ultrasonic inspection. During the ultrasonic inspection, a surface defect was found on the web for both stages. These defects were removed using local hand-benching. Subsequent ultrasonic inspection showed no defects.

The disk shot peening required a process development to reduce the level of the recast surfaces resulting from the EDM process. The peening process was used satisfactorily on these disks.

#### Work Planned

- Interface with Evaluation or Instrumentation Application which includes flame spraying on local surfaces for tack welding the instrumentation leads

- Review instrumentation drawings
- Continue coordination with manufacturing on second set of shroud hardware.

#### 2.4.8.4 Rotating Shaft and Seals Impeller

##### Impeller

Impeller manufacturing has been completed and is currently being reworked for instrumentation. Preparation for flame spraying, instrumentation application, and routing are proceeding.

Prior to final shot peening, the impeller was inspected for defects in the web using high-sensitivity ultrasonic techniques. No indications were found.

##### Inducer Seal Disk

The manufacture of the inducer seal disk has been completed. No rework for instrumentation is required. The part will be flame sprayed for instrumentation application and routing.

Prior to flame spray, the disk will be subjected to a high-sensitivity ultrasonic inspection to minimize possible material defects. The finished part is shown in Figure 2.4-18.

##### Interstage Disk

The manufacturing process for both interstage disks has been completed. No instrumentation rework is required for this part.

Prior to final shot peening, the disk for the core engine test was subjected to high-sensitivity ultrasonic inspection. No indications were found.

During manufacture of the second disk, fluorescent penetrant inspection revealed crack-like indications in the outer diameter of the rib that serves as a windage cover and retainer for the Stage 2 blade damper. Rework of the area to remove such indications has resumed in a scallop in the rib approximately 0.8 in. long x 0.25 in. deep. The function of the port would not be compromised by the scallop. This disk will be held as a spare.

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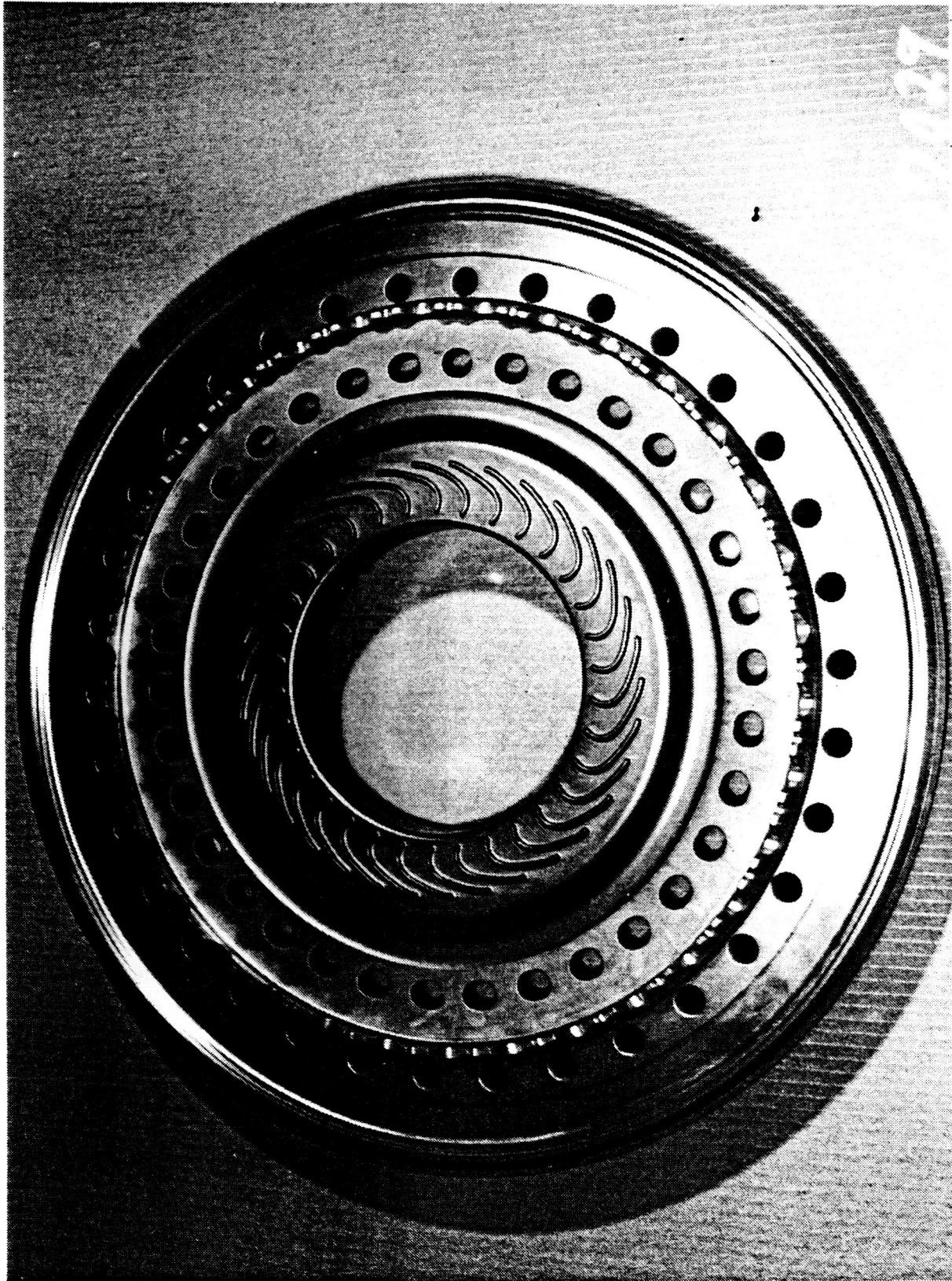


Figure 2.4-18. HPT Inducer Seal Disk.

#### Stage 1 Aft Blade Retainer

The René 95 Stage 1 blade retainer manufacture has been completed and is being reworked for instrumentation. Manufacture of the second retainer is continuing and is scheduled for delivery in early November.

#### Stage 2 Aft Blade Retainer

The Stage 2 blade retainer has been completed, including rework for instrumentation. The finished part is shown in Figure 2.4-19.

#### HP Shaft

The shaft has been completed and is shown in Figure 2.4-20.

#### Forward Outer Liner

The forward liner has been completed and is shown in Figure 2.4-21.

#### Aft Shaft/Seal Disk

The aft shaft/seal disk has been completed.

#### Inner Tube

The inner tube has been completed and is currently being shipped from the vendor.

#### Work Planned

- Complete all flame spraying of rotor parts for instrumentation application.
- Interface with evaluation and instrumentation personnel or instrumentation drawings.

#### 2.4.8.5.1 Stage 1 Nozzle Fabrication

#### Technical Progress

Progress has been achieved in improving delivery dates for the subassembly components for the Stage 1 nozzle fabrication.

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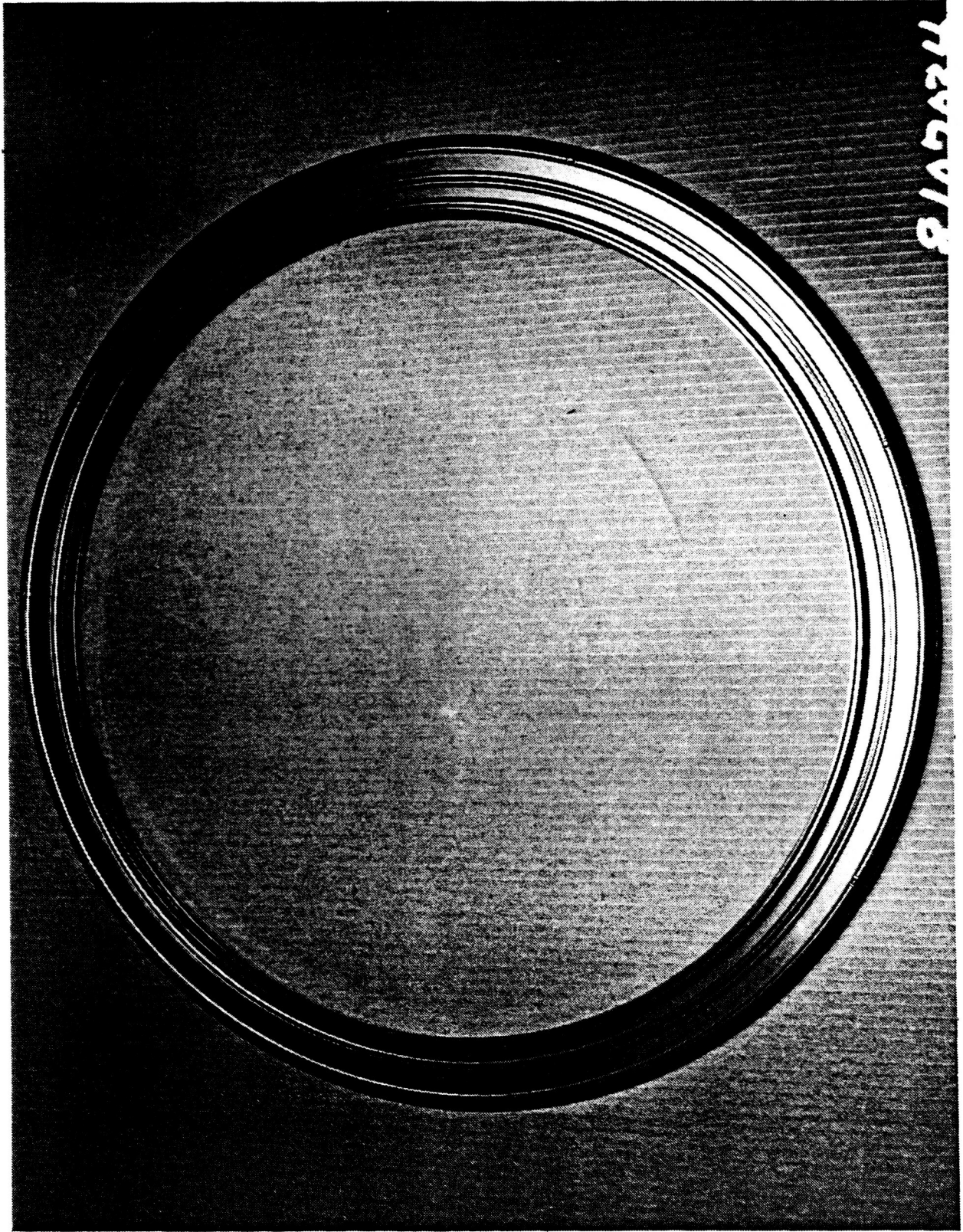


Figure 2.4-19. HPT Stage 2 Aft Blade Retainer.

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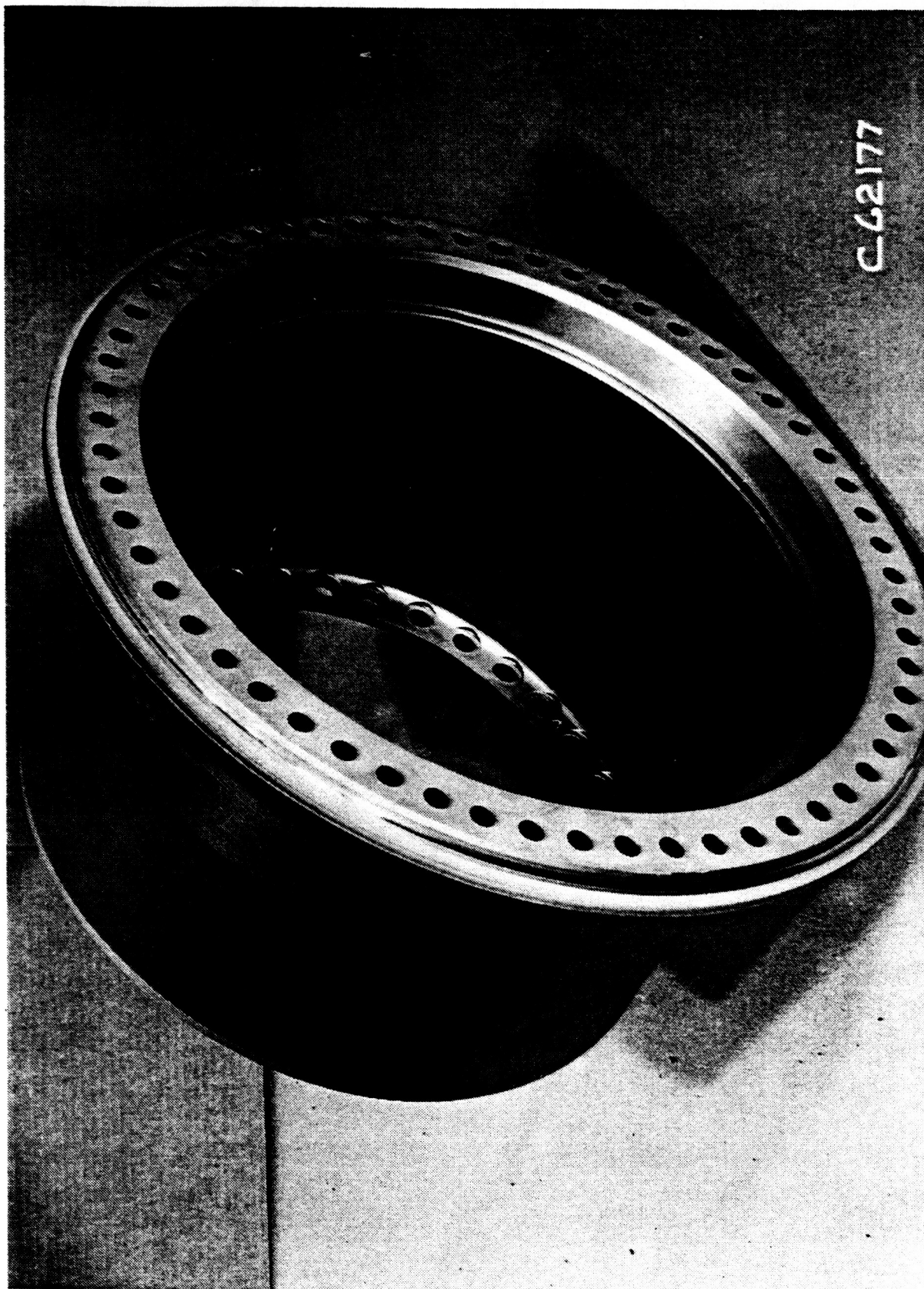


Figure 2.4-20. HPT Forward Shaft.

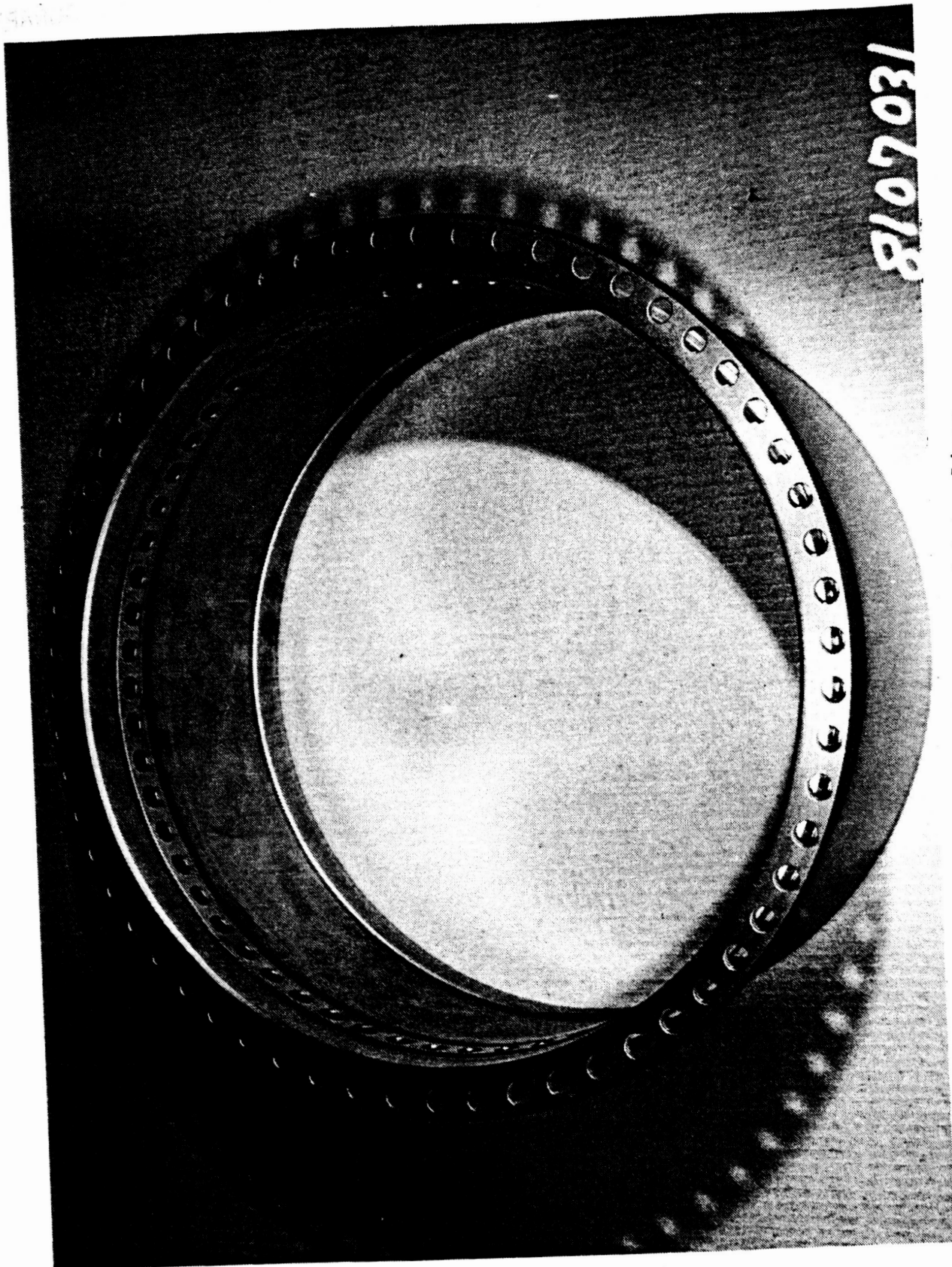


Figure 2.4-21. HPT Forward Outer Liner.

All components (except the inserts) presently are being used in the nozzle fabrication process.

Problems were encountered by the manufacturing vendor in the EDM process for the airfoil contour plunge position on the inner and outer bands. This effect was causing an interference with fitup between the airfoils and bands. Readjustment of the EDM plunge contour location to its proper position was made, allowing the airfoils to be assembled in the inner and outer bands.

Stage 1 nozzle fabrication has been completed by brazing the airfoils and band impingement plates. Machining of the flanges, band ends, and EDM of the band seal grooves for the flowpath seals remains to be done.

Vane and band instrumentation rework has been completed, and these parts will be included on the first set of engine hardware for the core and ICLS testing.

Completion of the first set of Stage 1 nozzle is expected in early November 1981.

#### Work Planned

- Complete the fabrication of the first set of nozzles for core engine testing.
- Initiate the second set of nozzle fabrication.
- Interface with the evaluation on instrumentation rework application for reworked vanes and bands.

#### 2.4.8.5.2 Stage 2 Nozzle Diaphragm Fabrication

##### Technical Progress

##### Airfoil

The Stage 2 vane airfoil core printout redesign significantly increased the core yield. The redesign and subsequent core die rework consisted of increased core printout radius, plus removal of core overhang material used as the airfoil core support.

Fifty airfoil castings were accepted by Engineering for nozzle fabrication. The subsequent airfoil process consisted of grinding the trailing edge to proper dimensions and machining the inner and outer ends. The airfoils were then coated with the PVD process for environmental protection. These vanes are presently being assembled in the inner and outer band segments for the brazing operation.

Three airfoils are presently being reworked for instrumentation application. This consists of EDM grooves in the airfoil for subsequent application of embedded thermocouples in these grooves.

#### Outer Band

All band castings have been delivered for machining. The bands have been EDM plunged using the actual airfoil casting contour. This allows an improved control of the gap formed between the surface along the band plunge and airfoil contour.

#### Inner Band

Problems encountered by the vendor during the band casting process resulted in late delivery of this part. The main problems consisted of metallurgical rejects due to cold sheets which were detected during the metallurgical and FPI inspections. Subsequent casting showed improved yields resulting from process variation. Presently adequate castings are available for the core engine. These castings have also been processed through the EDM plunge of the airfoil contour, plus EDM of the cooling holes located in the forward portion of the band.

#### Impingement Inserts

Problems with the manufacture of insert tooling in order to produce the proper insert contour forms have caused schedule delays relative to the original deliveries. Present promised delivery date is acceptable. In order to assure no further delays, Purchasing and Engineering are maintaining close interface with the vendor.

### Nozzle Fabrication

The 50 airfoils are being brazed to 25 paired inner and outer bands. Measured throat areas indicate values to be on the higher levels permitted but still within blueprint.

### Work Planned

- Complete the first set of nozzle fabrication.
- Instrument airfoil and bands for engine tests.

### 2.4.8.6 Support Structures and Inducer Fabrication

#### Technical Progress

#### Static Structures

With the exception of the forward outer casing, all machining operations for static support structures have been completed. Parts requiring manufacturing rework for instrumentation application are presently being completed. The forward casing delivery date is scheduled for the second week of October 1981.

#### Active Clearance Control Manifold

The fabrication of the manifolds is progressing on schedule. The plenums have been formed and welded and are in heat treat. Fabrication of the parts welded to the manifolds is continuing and is on schedule.

#### Ceramic Shrouds

The ceramic shroud castings were successfully completed. The first set of castings for the core engine has progressed through the application of the ceramic coating and partial machining of the hooks and flowpath surfaces. Final machining and delivery is expected by the first week in October.

#### Stage 2 Solid Shrouds

Twenty-nine castings have been spray coated (on flowpath surface) with UPD CoNiCrAlY; completion of final machining is planned for the first week in October.

Worked Planned

- Interface with evaluation on assemblies of the Stage 1 nozzle and support and the Stage 2 nozzle and shroud.
- Review the instrumentation drawings.
- Continue coordination with manufacturing on a second set of shroud hardware.

## 2.5 LOW PRESSURE TURBINE

### Overall Objectives

The objective of the low pressure turbine development effort is to provide a highly efficient LP turbine having material and configuration features that provide maximum opportunity for mechanical success.

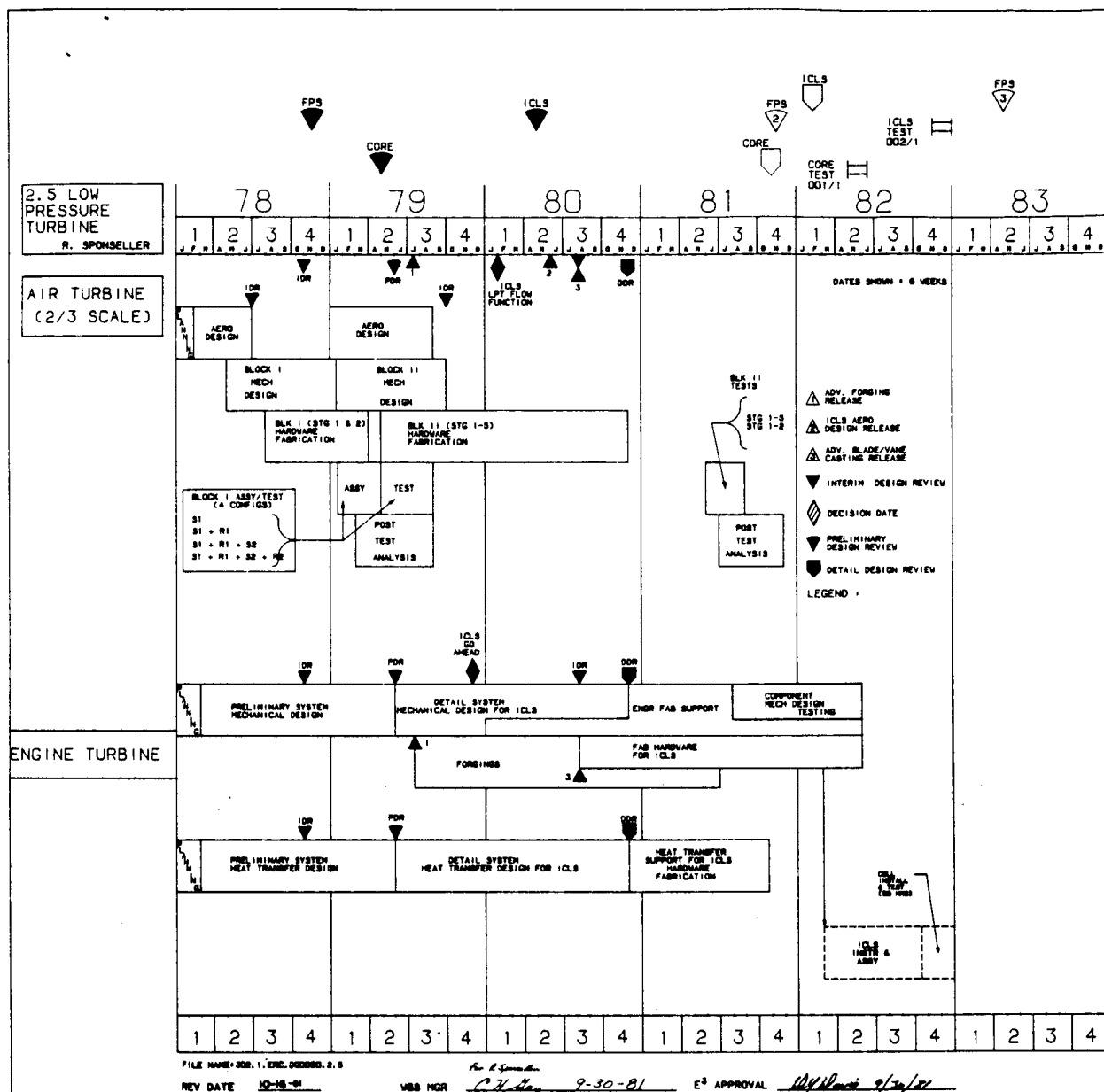
Performance improvements will be aimed at achieving the highest possible turbine efficiency compatible with moderate-to-high turbine aerodynamic loading. The FPS low pressure turbine efficiency goal is 0.917 at Mach = 0.8, 35,000 feet, standard day, maximum climb power setting. Also considered are off-design operating points in order to ensure a viable system throughout the operating regime of the engine.

Mechanical integrity is a major goal of the LP turbine mechanical design. The aeromechanical goal is that the blades and vanes have no instabilities within the operating range of the turbine.

### Development Approach (Reference WBS 2.5 Schedule Sheet)

The overall development plan for the LP turbine provides a systematic approach to its design. This involves (1) early identification of critical areas and (2) component design that can accommodate the critical requirements. The major LP turbine development areas are (1) aerodynamic design and air turbine evaluation; (2) system and mechanical design, which is carried out concurrently with the aero work; (3) hardware fabrication; (4) component bench tests; and (5) instrumentation, assembly, and engine test.

Preliminary aero blade and vane design for the initial flowpath comprised the major initial effort. Other mechanical and heat transfer design paralleled this aero effort, and an overall LP turbine IDR was held in November 1978 and was followed by the LP turbine PDR in May 1979. Block I air turbine testing of Stages 1 and 2 was completed in August 1979. Aero modifications were factored into Block II blading and sequentially released over the period from January through March 1980. An IDR of this work was



held in March 1980. Procurement of Block II hardware has been completed. Air turbine tests of all five LP turbine stages and two-stage air turbine testing have been completed and data analysis is underway.

Detailed mechanical design of the engine turbine was initiated in June 1979 after the PDR milestone. The next major milestone was the ICLS go-ahead decision given in November 1979, ahead of the scheduled January 1980 date. Continuing detail mechanical design, incorporating the Block II airfoil configurations was summarized for an August 1980 IDR, and a DDR was held in December 1980. Release of fabrication orders began in September 1980 with cast parts, although advanced forging releases has been made as early as June 1979. All ICLS engine hardware has been released for procurement and initial finished parts are starting to be received. The earliest manufactured blades and vanes will be utilized for bench testing. Bench testing will allow identification of responsive locations on the airfoils, where instrumentation will be applied. All components will then be assembled into the ICLS demonstrator; testing is scheduled for the last quarter of 1982.

#### 2.5.1 LPT Aerodynamic Design

##### Technical Progress

During this reporting period, the aero portions of the LP turbine Detailed Design Report and the LPT Hardware Specification Document were submitted and all Block II rig testing was completed.

##### Block II Air Turbine Test

Testing of the Block II two-stage group, Figure 2.5-1, was completed June 19, 1981. The following items were accomplished in the five runs on this rig:

- Performance mapping over a matrix of six pressure ratios by six values of blade-jet speed ratio
- Reynold's number excursion

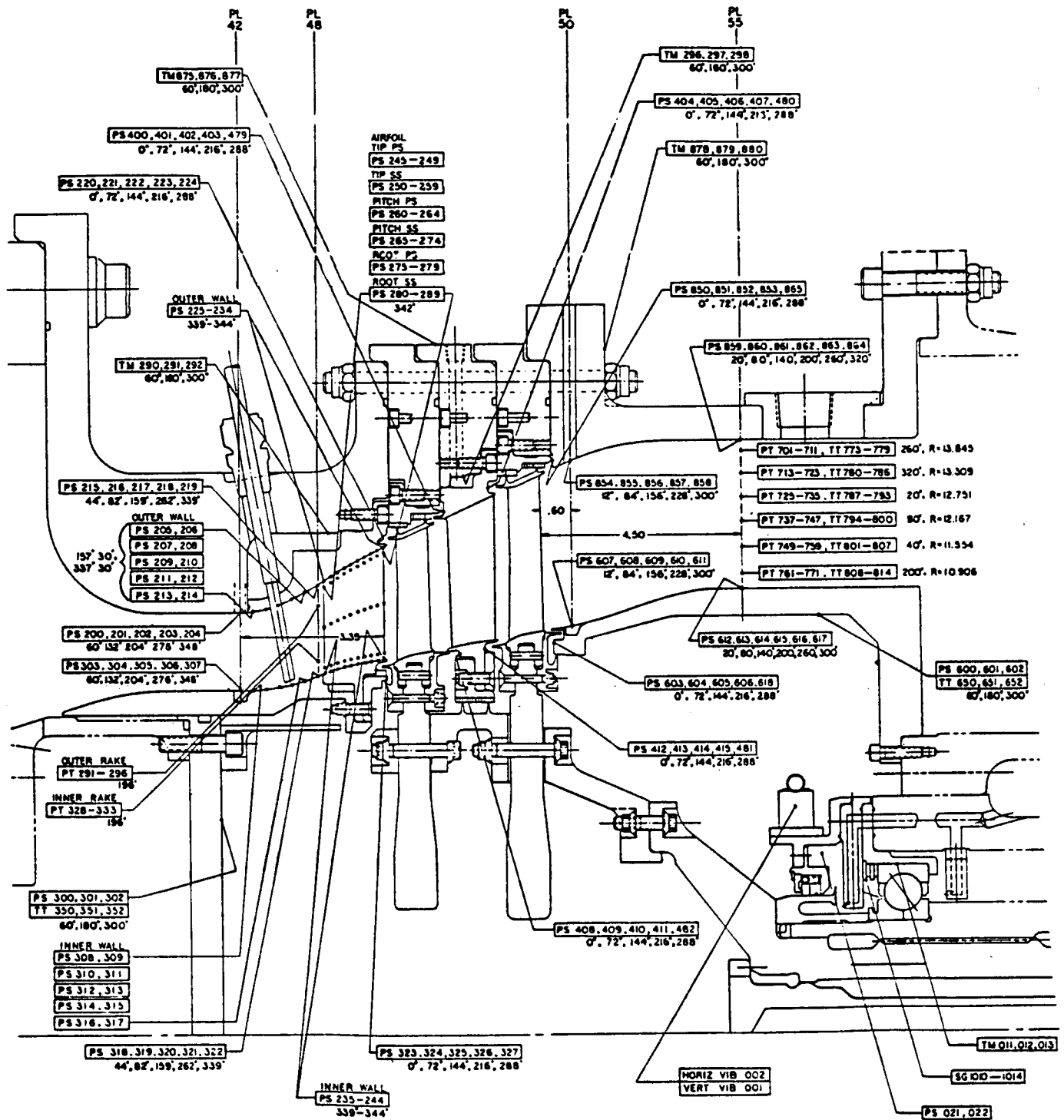


Figure 2.5-1. Scaled Test Vehicle Instrumentation Drawing, Two-Stage Configuration.

- Evaluation of the loss associated with 14  $P_T/T_T$  inter turbine probes to be used in the ICLS.
- Detailed rotor exit surveys at design point, with and without inter-turbine probes immersed, and at a Reynolds number simulating 35,000 feet altitude.

Two-stage group efficiency was 0.891 based on measured torque, speed, flow, and pressure ratio. This represents a gain of approximately 0.75% over the Block I group efficiency at the Block II group loading ( $\Delta h/2u_p^2$ ) of 1.68.

Figure 2.5-2 presents two-stage group efficiency versus group loading for the Block II compared to the Block I. The 0.75% efficiency gain noted at design loading ( $\psi = 1.68$ ) is attributable to the following design modifications incorporated into Block II as a result of Block I data analysis:

1. Higher aspect ratio and solidity in Stage 1 vane
2. Improved flowpath overlap geometry
3. Improved airfoil design.

It is interesting to note that the improved airfoils (item 3) seem to be more tolerant to negative incidence as evidenced by the relatively larger efficiency gains at loadings less than design loadings.

The magnitude of the measured efficiency change is consistent with that anticipated for Block II improvements as documented in the LPT Block II DDR.

A loss of 1.8% in two-stage group efficiency (accompanied by a 1.6% drop in inlet flow function) was measured when the 14  $P_T/T_T$  probes were immersed into the flow stream. This corresponds to a loss of 0.77% in the five-stage group efficiency and about 0.5% in ICLS sfc. It is intended that this be incorporated into the ICLS cycle deck as an instrumentation loss.

Testing of the Block II five-stage vehicle, Figure 2.5-3, was completed September 11, 1981. The following items were accomplished in the five runs on this rig:

- Performance mapping over a range of pressure ratios and speeds which (within the operational limitations of the test facility) yielded data across the full extent of the ICLS LPT operating line, from maximum climb to flight-idle.

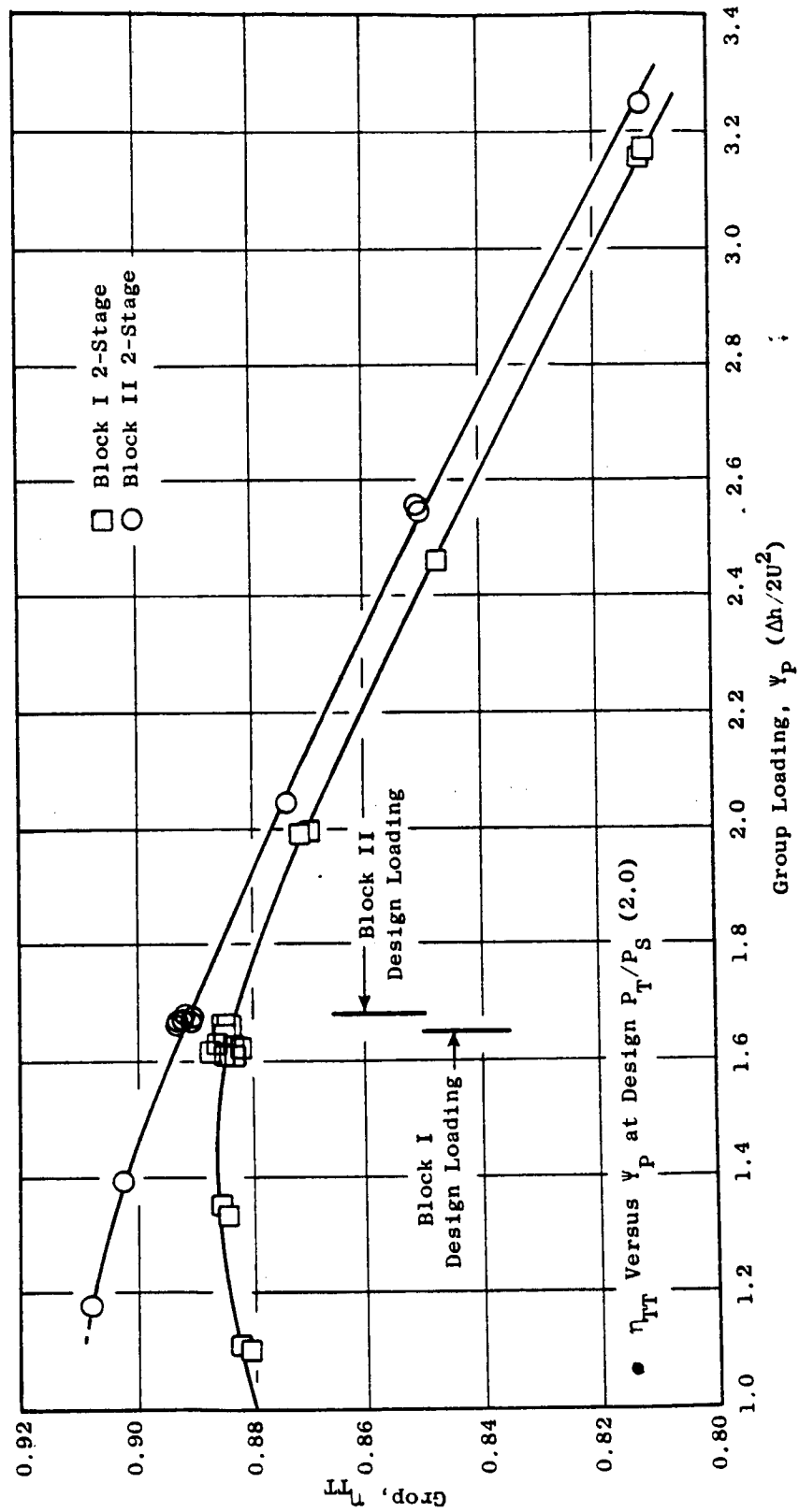


Figure 2.5-2. <sup>3</sup> E Low Pressure Turbine 2-Stage Efficiency Versus Loading.



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- Reynolds number excursion, covering a range of Reynolds numbers from one equivalent to the ICLS LPT at sea level takeoff to one equivalent to the ICLS LPT at the Mach 0.8, 35,000 feet maximum climb (design point) conditions.

Preliminary design point efficiency for the five-stage vehicle is 0.919. the following tabulation compares this result with a pretest estimate (based on extrapolations from Block I test results) made for the 1980 DDR:

	<u>1980 Estimate</u>	<u>1981 Rig Test</u>
$\eta_{TT}$ base	91.5%	91.9%
$\Delta\eta$ purge air	+0.1	+0.1
$\Delta\eta$ Reynolds number	<u>-0.7</u>	<u>-0.7</u>
$\eta_{TT}$ at M.8/35K max climb	90.9%	91.3%

These are relative to program goals (M 0.8/35K maximum climb) of 91.1% for the ICLS and 91.7% for the FPS.

It should be noted that the Reynolds number correction carried in this tabulation is an estimate pending final assimilation of the rig Reynolds number test data. Preliminary test results indicate, however, that the estimated 0.7% penalty in five-stage group efficiency for altitude operation is very representative.

Figure 2.5-4 presents five-stage group efficiency versus group loading at the design total-to-static pressure ratio of 4.76.

Work on the Block II Test Memo is underway.

Work Planned

During the next reporting period, the Block II Test Memo and the LPT Rig Test and Performance Report will be issued.

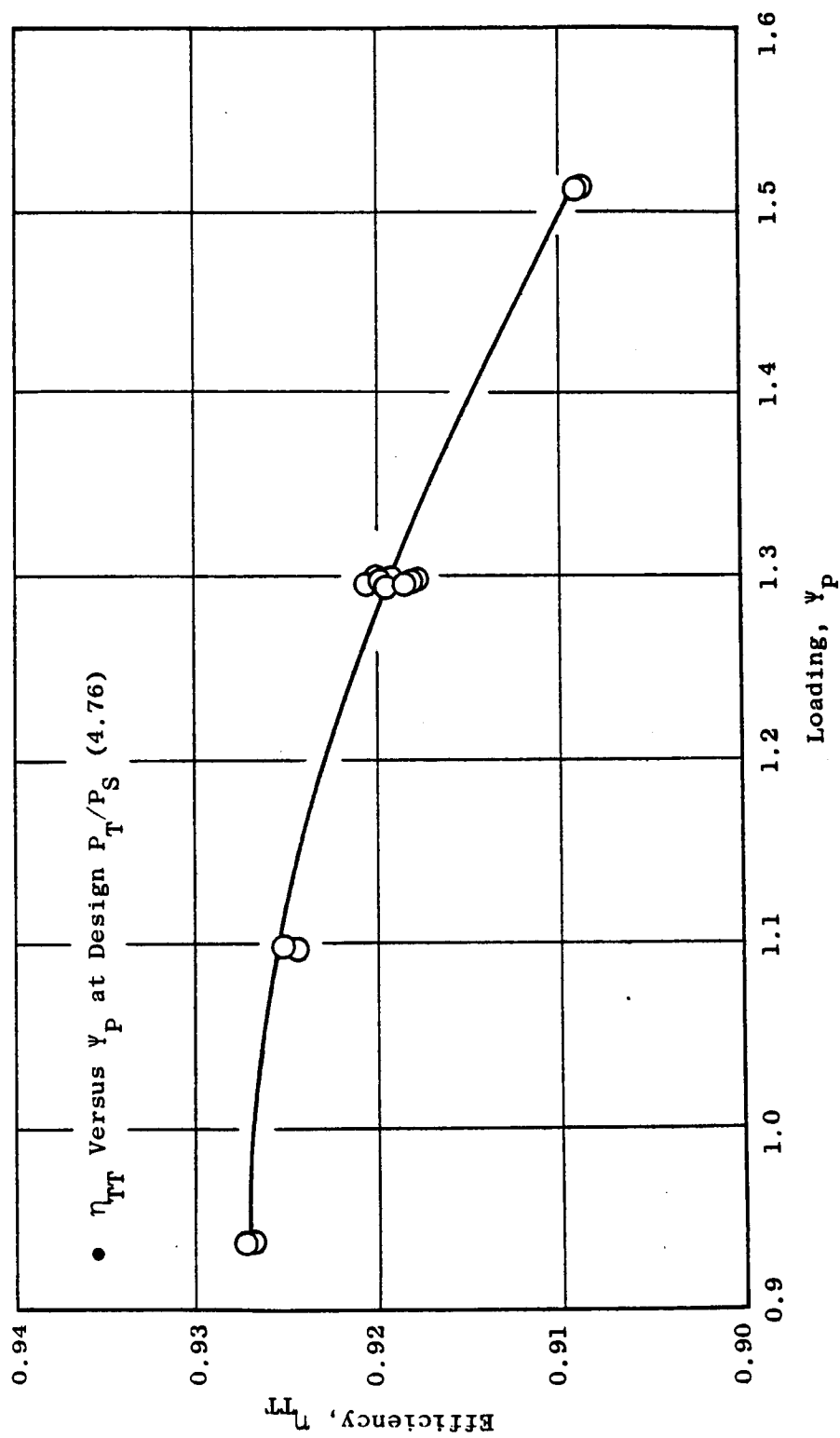


Figure 2.5-4. E<sup>3</sup> Low Pressure Turbine 5-Stage Rig, Efficiency Versus Loading.

### 2.5.2 Low Pressure Turbine Heat Transfer Design

#### Technical Progress

During this report period, few remaining items that were required to complete the detail design work on the low pressure turbine were completed.

These items include:

- Detail design report
- Technical specification document
- Updated engine start analysis
- Updated rotor structure thermal analysis
- ICLS rotor/stator casing temperature analysis

#### Rotor Structure Thermal Model Update

With several changes having been made to the rotor structure, it became necessary to update the thermal analysis. The new thermal model is shown in Figure 2.5-5. The model included the three-dimensional effects of the bolts, dovetail, scallops, and flange slot cooling. Also, the free convection heat transfer coefficients were evaluated around the rotor disks in the thermal model temperature analysis. The coefficients that were used for the free convection analysis were based on the engine experience.

The thermal analysis of the E<sup>3</sup> LPT has now been completed. The temperatures have not changed significantly except where the disk bores have been sized down. The transient response is quicker at these locations. The model was used to define the rotor growth for both the ICLS idle-maximum takeoff transient and the FPS takeoff/climb/cruise mission. In order to match the clearance of the rotor and casing, the matching thermal analysis of the casing was also completed. Presented below is the complete list of transients that were analyzed for the low pressure turbine.

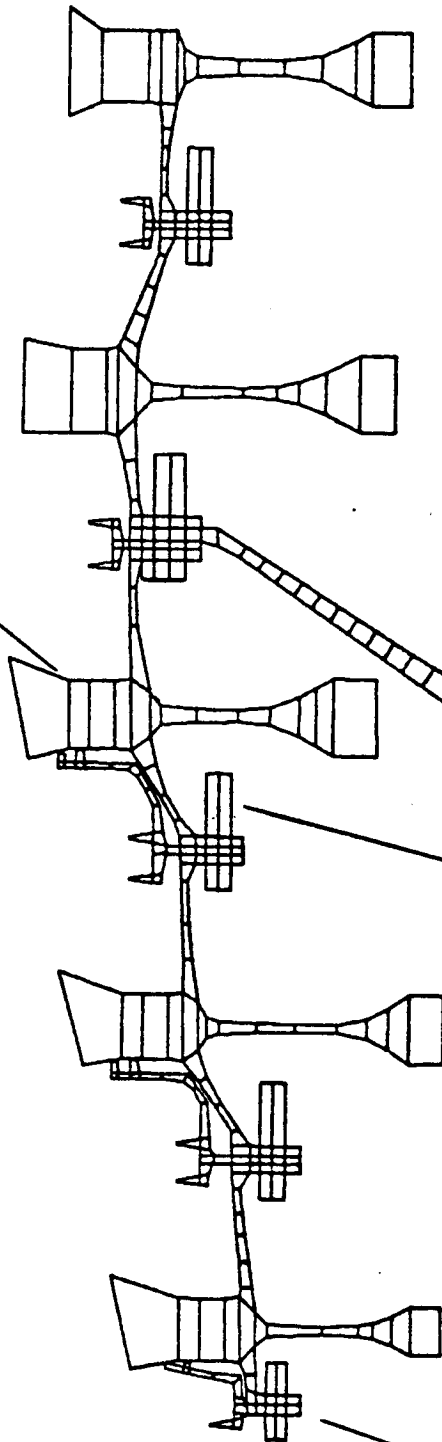
- ICLS rotor takeoff accel-decel
- ICLS casing takeoff accel-decel with minimum casing cooling

279 NODES  
80 BOUNDARY CONDITIONS (TIME DEPENDENT)  
1116 TEMPERATURES/TIME STEP

3-D DOVETAIL  
SIMULATION  
(5 PLACES)

3-D BOLT  
SIMULATION  
(5 PLACES)

FLANGE SLOT  
COOLING  
(4 PLACES)



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Figure 2.5-5. E<sup>3</sup> Low Pressure Turbine Detailed Thermal Model Update.

- ICLS casing takeoff accel-decel with maximum casing cooling
- ICLS casing takeoff accel-decel with minimum casing cooling on Stages 1, 2, and 3 and no cooling on Stages 4 and 5
- FPS rotor takeoff/climb/cruise mission
- FPS rotor takeoff/climb/hot rotor reburst
- FPS casing takeoff/climb/cruise mission with minimum cooling
- FPS casing takeoff/climb/cruise mission with maximum cooling
- FPS casing takeoff/climb/cruise mission with maximum cooling on Stages 1, 2, and 3 and no cooling on Stages 4 and 5
- FPS casing takeoff/climb/hot rotor reburst

This transient data will be analyzed by mechanical design to establish buildup and cruise clearances.

#### Work Planed

None.

#### 2.5.3.2 LPT Rotor Mechanical Design

##### Technical Progress

Work carried out during this reporting period was related primarily to clearance calculation updates, submission of final report drafts on the LPT detail design and the LPT test hardware specification, and ICLS associated calculations. No major changes have been made to the rotor design as presented in the March 1981 Semiannual Report.

#### Stage 1 Blade Start Transient

An analysis was completed to assess the effect of startup on the LCF life of the Stage 1 low pressure turbine blade. The leading edge was found to be the limiting location. It reached a compressive stress of 25 ksi shortly after combustor light-off and a tensile stress of 6 ksi during a decel from maximum takeoff to ground idle. The resulting LCF life at 70% span was more than 100,000 cycles versus 18,000 required.

### Rotor/Stator Clearance Study

Heat Transfer completed a full mission study of the rotor during this report period. The resulting temperatures are being used to recheck the limiting locations on the LPT disks to determine the severity of thrust reverse on LCF life and to finalize rotor/stator clearances. This full mission study of the rotor is combined with a full mission study of the stator and is discussed in Section 2.5.3.3 under LPT Rotor/Stator Radial clearances.

### LPT Rotor Instrumentation Rework

Coordination between Design, Evaluation, and Instrumentation Planning for ICLS LPT Rotor was conducted during this report period. Overall instrumentation rework requirements for the ICLS LPT rotor has been identified.

Circumferential locations for rotor instrumentation rework were defined. Shop modification drawings for Stages 1 and 2 rotor seals and Stages 1 through 4 disks were then issued. No instrumentation rework is required on the Stage 5 disk or Stages 3, 4, or 5 rotor seals, thus all rework required on the rotor spool has been defined.

Preliminary layouts of instrumentation patterns to be applied to the blades have been initiated. Plans are to instrument eight blades of each stage with combination of thermocouples and strain gages. Bench tests will be conducted to establish the most desirable strain gage location prior to issuing the blade rework drawings.

### Work Planned

- This work task has now been completed.
- Final blade instrumentation rework and ICLS buildup work will be carried out under 2.5.3.4.

### 2.5.3.3 LPT Stator Mechanical Design

#### Technical Progress

##### LPT Shroud Modification

Drafting layouts were completed which identified shroud modifications that improve the radial and axial fit of the shrouds into the casing/nozzle assembly.

##### Insulation Blankets

An additional insulation blanket was identified over the Stage 1 nozzle. The basic design is the same as for all the other 13 previously identified locations in the LPT; i.e., an insulation material encased in INCO 600 foil.

##### LPT Stator Instrumentation Rework

Coordination between design, evaluation, and instrumentation planning for ICLS LPT stator was conducted during this report period. Overall instrumentation rework requirements for ICLS LPT stator has been identified. Instrumentation bosses have been incorporated into the LPT casing. Layout drawings to define stator shop modification drawings are in process. The plan remains to incorporate all instrumentation rework into the manufacturing cycle of the various LPT parts.

##### LPT Rotor/Stator Radial Clearances

An up-to-date operating clearance analysis was initiated during this reporting period to review the LPT rotor/stator operating conditions. This analysis has been used to study ICLS LPT operating clearances/rub between the blade tip shroud seal teeth and the shroud honeycomb seals. From this study, cold radial clearances will be set for the ICLS LPT. A FPS radial clearance analysis and study is in progress and will be used to predict FPS full cycle radial operating clearances.

The heat transfer analysis for both the rotor and stator models are completed and will be used to complete the clearance analysis work. A computer model which defines all significant radial gaps and calculates clearances,

based on separate rotor and stator growth values, is operational and has resulted in data used in the ICLS LPT operating clearance analysis. FPS clearance analysis will follow the ICLS clearance work.

Heat transfer analysis indicated a need to add a splash shield directly over the outer duct support and under each of the six 5th stage air ports in the HPT aft case. The effect of the shield is to minimize circumferential temperature gradients in the cone of the support. The addition of the shield required a slight change to the support to eliminate a possible interference. A finite element analysis was used to verify the integrity of the support with the change included.

Another analysis of the outer duct support was done based on results of a heat transfer analysis of the HPT stator/Stage 1 nozzle subassembly, which included the effects of the added splash shield. This analysis predicted that the potential 5 mil gap between the support area and the HPT casing will be reduced to 2 mils. With an assembly interference of 0 to 2 mils (radial), this potential gap is no longer considered a problem.

The seal slot depths for the inner and outer ducts as well as the Stage 1 nozzle were recalculated using less conservative assumptions in an effort to reduce the slot depths for ease of manufacture and also cost reduction. The new calculations reduced the slot depths by approximately 0.100 inch.

The air tube material was changed from 6605 to 321 stainless steel and the assembly fit changed to  $\pm 0.001$  to assure a more positive seal of 5th stage air. These changes have been incorporated into the order for the tubes.

All drawings have been issued and parts placed on order.

#### Worked Planned

All major work planned in this section is being concluded with clearance documentation also being completed.

Coordination of the shroud and insulation modification as well as detail definition of instrumentation rework will be carried out under 2.5.3.4.

#### 2.5.3.4 LPT Hardware and Test Support

##### Technical Progress

##### LPT Hardware Scheduling

A detailed flow chart of the LPT hardware scheduling was initiated during this report period, and a preliminary plan was completed. This flow chart shows the target dates for delivery of casting and machined parts in partial lots in order to meet instrumentation rework, bench testing, and ICLS assembly schedules. Negotiations to accomplish required delivery dates were initiated and have been effective. All anticipated delivery dates are currently within scheduled requirements.

##### LPT Assembly Drawings and Balance Requirements

Coordination between Design, Evaluation, Drafting, and Assembly Planning was initiated to identify LPT assembly drawing requirements; particularly to satisfy buildup, balance, and clearance call-out requirements. This effort was directed toward minimizing the number and complexity of the assembly drawings.

Drafting dates were established for completion of the LPT drawings.

Preliminary check prints for the LPT assembly and the LPT nozzle 1 assembly are 85% complete. A stack-up drawing of the LPT is 90% complete and will provide a basis for the LPT assembly clearance drawing, which is scheduled for issue in mid October 1981.

##### Work Planned

- Continue to provide engineering support to vendors
- Incorporate valid vendor requested changes into the detail drawings
- Complete assembly and clearance drawings
- Continue instrumentation rework drawings.

#### 2.5.4 LPT Mechanical Design Testing

##### Technical Progress

##### Blade Bench Tests

Blade fixtures for hot fatigue testing and vibration testing were received during this reporting period. It is expected that testing can begin in early 1982 upon receipt of machined blades.

##### Nozzle Bench Tests

Planning has begun with reviews of the requirements for nozzle bench tests. Prior experience of nozzle bench tests plus engine experience and the correlation of bench data with engine data will be incorporated in the test plans.

##### Work Planned

- Finalized nozzle test plans and initiate facility work
- Initiate blade bench testing; fixture fit-up checks, sample instrumentation, frequency evaluation.

#### 2.5.6.1 LPT Rotor (Bench Blades and Tooling)

##### Technical Progress

##### Castings

Significant progress was made on the low pressure turbine blade castings during this reporting period. Several trips were made to the vendor (Howmet, Misco-Whitehall Division) to review layout inspection reports and blade tooling. Sample castings were obtained which showed:

- Airfoil sections smooth and well blended
- Leading and trailing edges smooth and uniform in thickness
- Smooth and continuous fillet blends at airfoil tip and root
- Good thickness control of shroud and platform overhangs

Some minor tooling rework was required to correct the Stages 1 through 3 blade retainer hooks to the drawing dimensions. Also some rework was done on Stages 1 through 4 to increase the tip shroud cutter teeth dimensions to retain adequate stock for later machining operations.

The tooling rework was completed and layout inspection reports were submitted for the reworked areas. In addition, the vendor submitted a new metallurgy study for the Stage 5 blade with improved microporosity results from a revised gating system. A sample grain blade from each stage was etched to evaluate grain size and their photos were also included in the report as shown in Figures 2.5-6 and 2.5-7. The reports were reviewed and found acceptable, therefore the vendor was released to cast all five stages of low pressure turbine blades. It is estimated that the first set of castings will be available in mid October 1981.

#### Machining

All five stages of low pressure turbine blades will have thermal-sprayed Triballoy T800 hard coat on the tip shroud interlock surfaces. The interlock surface will be rough ground at the machine vendor, sent to the thermal spray vendor for the hard coat, then returned to the machining vendor for final Z-form grinding.

The tip shrouds will be machined to two different widths to avoid fit-up problems at assembly. The different widths will provide adjustment necessary to eliminate manufacturing tolerance stack-up.

#### Work Planned

- Obtain blade castings
- Initiate and monitor machining vendor progress

#### 2.5.6.2 LPT Stage 1 Nozzle

#### Technical Progress

Nozzle wax dies have been completed and solid wax patterns produced for engineering review. Figure 2.5.8 shows one of these sample wax patterns.

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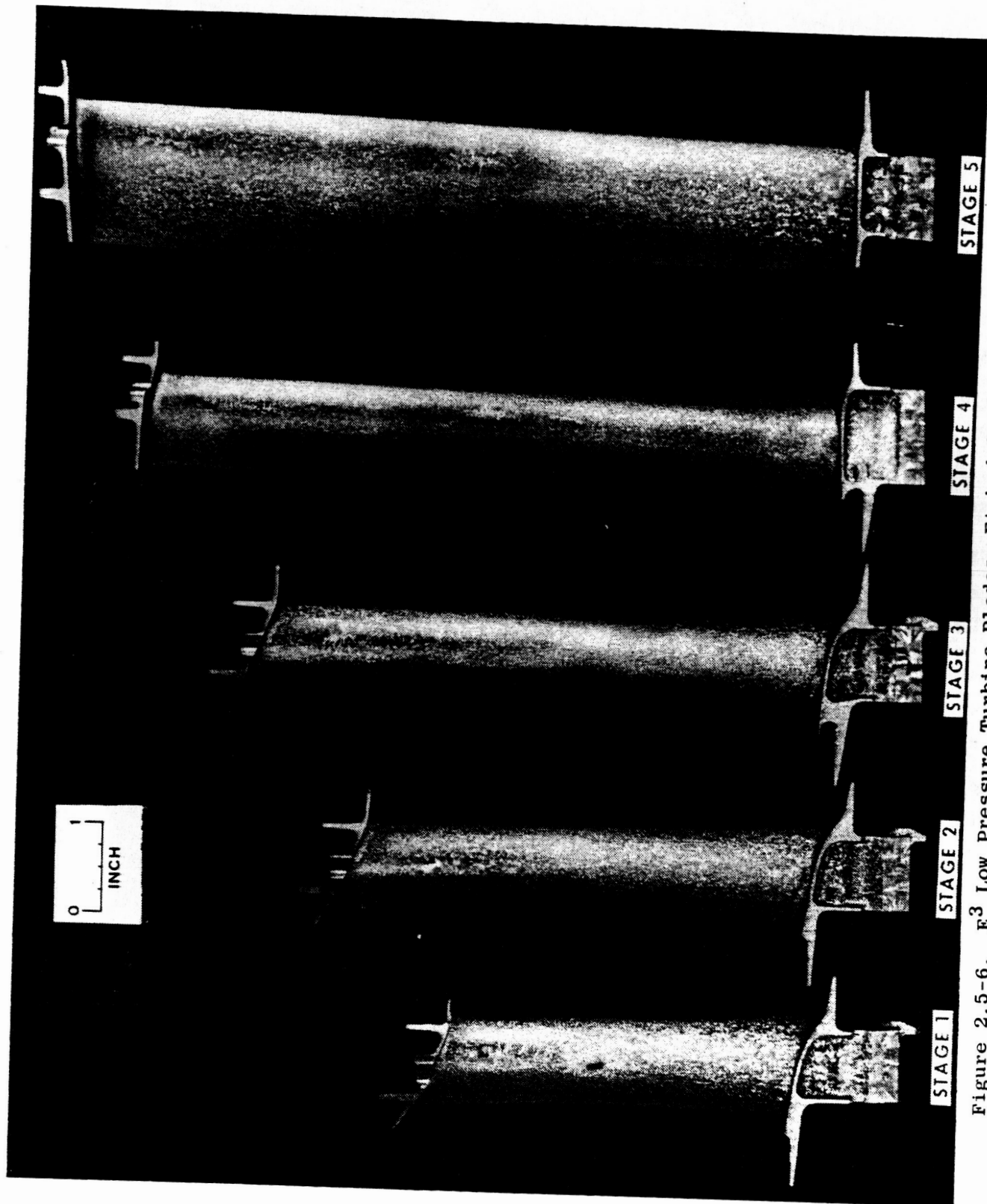


Figure 2.5-6. E3 Low Pressure Turbine Blades; Etched Castings; Concave Side.

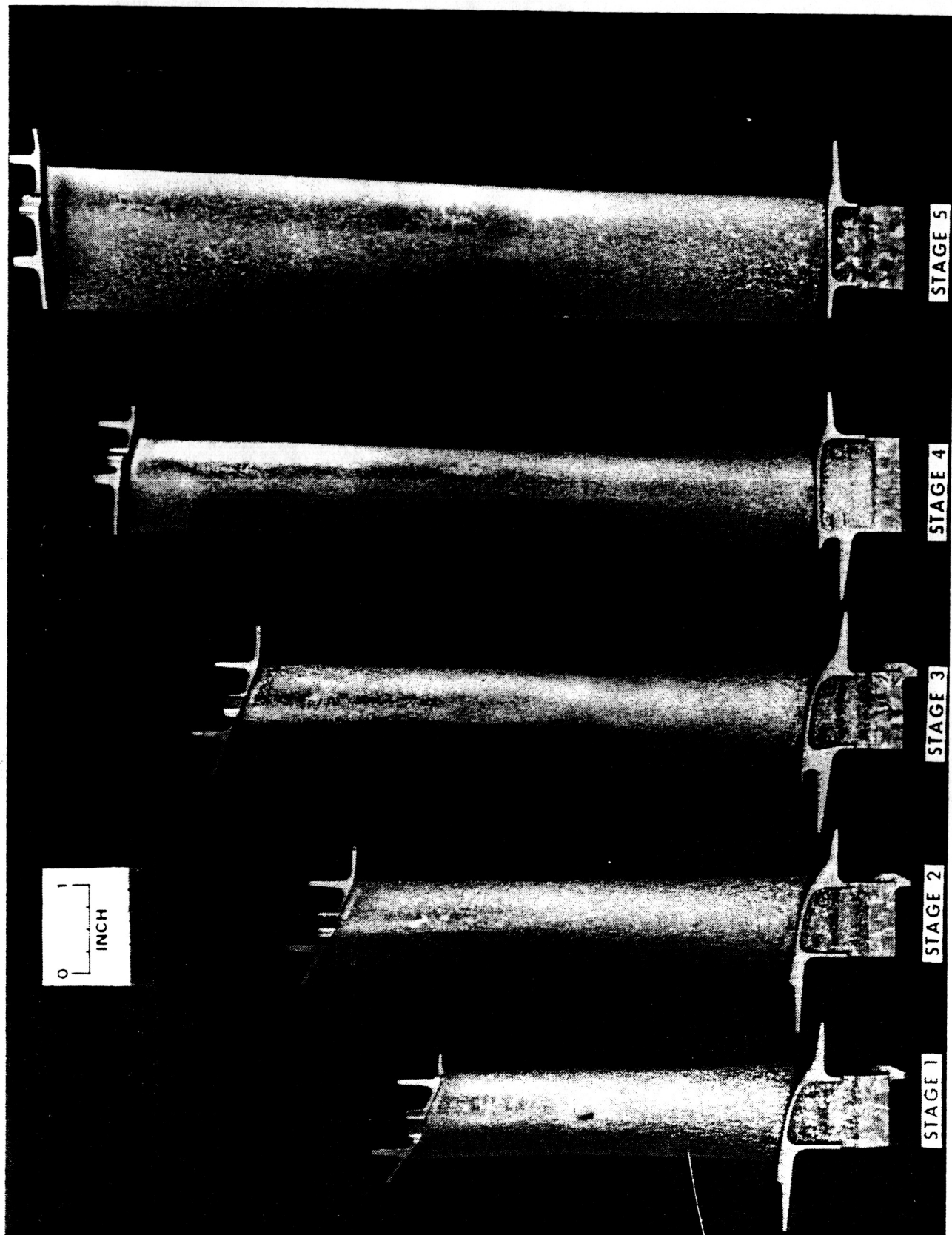


Figure 2.5-7. E<sup>3</sup> Low Pressure Turbine Blades; Etched Castings; Convex Side.

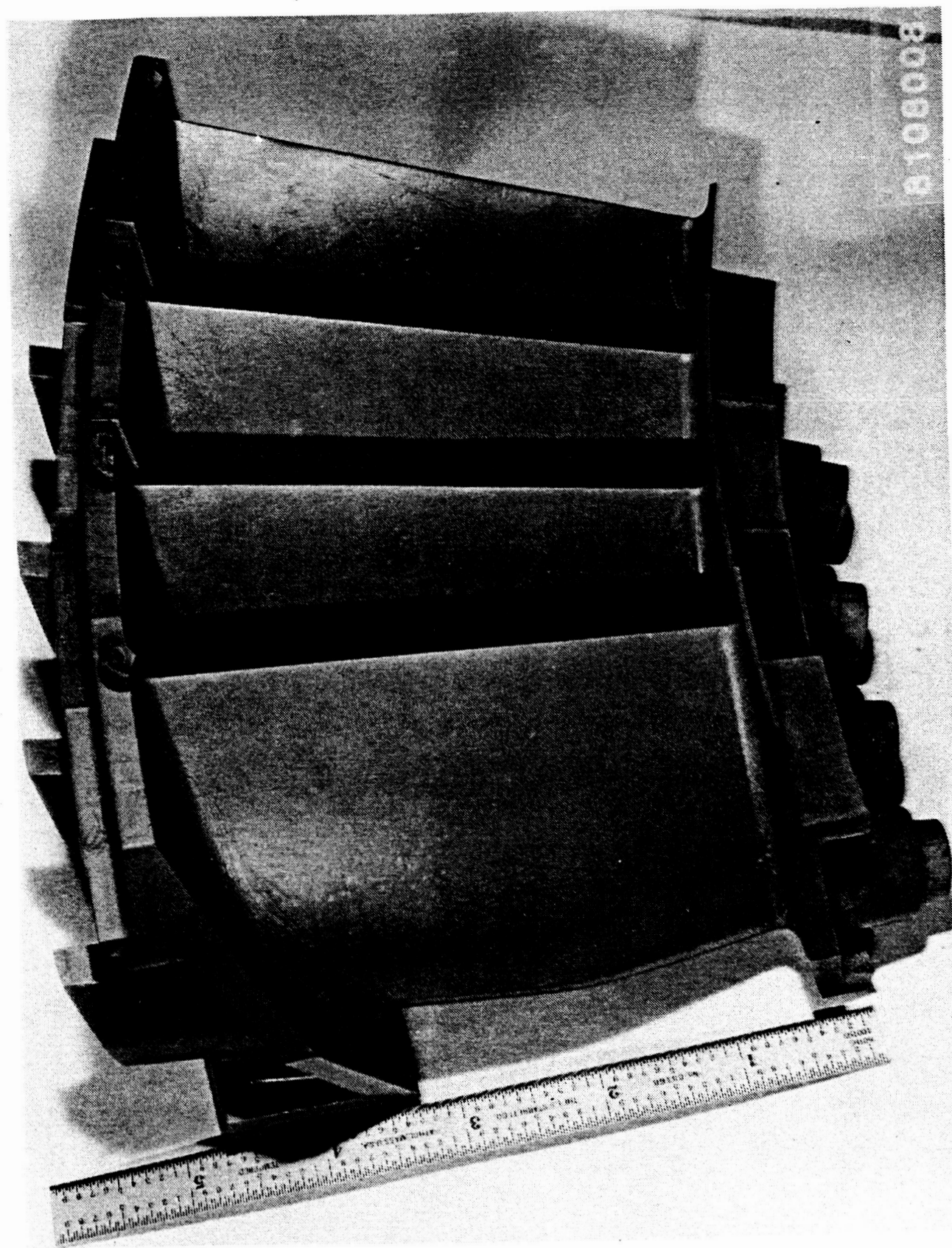


Figure 2.5-8. E<sup>3</sup> Low Pressure Turbine Stage 1 Nozzle Segment - Sample Wax Pattern.

Minor drawing discrepancies were then transmitted to the casting and tooling vendors. Completion of the nozzle core dies has been delayed due to complications. This has reduced the time available for TRW to supply castings as promised. However, sufficient time still remains to machine the nozzles, rework the instrumentation, and meet the assembly date.

Several changes have been made to the nozzle casting drawing since the last report. Many of the changes were vendor requested or suggested to reduce costs such as: (1) designing for a common core, (2) common No. 2 and 3 vanes in the four vane segment, and (3) additional definition in a transition area in the airfoil cavity.

Development Machining Operation (DMO) at GE has done initial planning for the Stage 1 nozzle machining. Several recommendations to the machining drawing have been based on manufacturing input and have been incorporated by DCID.

#### Work Planned

- Work with casting vendor to supply nozzle castings on schedule
- Start nozzle machining; provide engineering support
- Issue nozzle instrumentation rework drawings
- Trial fit nozzle machinings with attaching hardware
- Flow test machined nozzle.

#### 2.5.6.3 LPT Stages 2 Through 5 Nozzle Fabrication

##### Nozzle Castings

Several vendor requested changes have been incorporated into the nozzle casting drawings by DCID. Wax patterns have been reviewed by engineering on all four stages as has the first piece layout inspection report. The casting vendor (Misco-Whitehall) has been released to produce 1.3 engine sets of all four stages, and deliver castings by mid October 1981. Photographs of initial castings for Stages 2 and 3 nozzles and of a wax pattern of Stage 5 are shown in Figures 2.5-9, 2.5-10, and 2.5-11, respectively.

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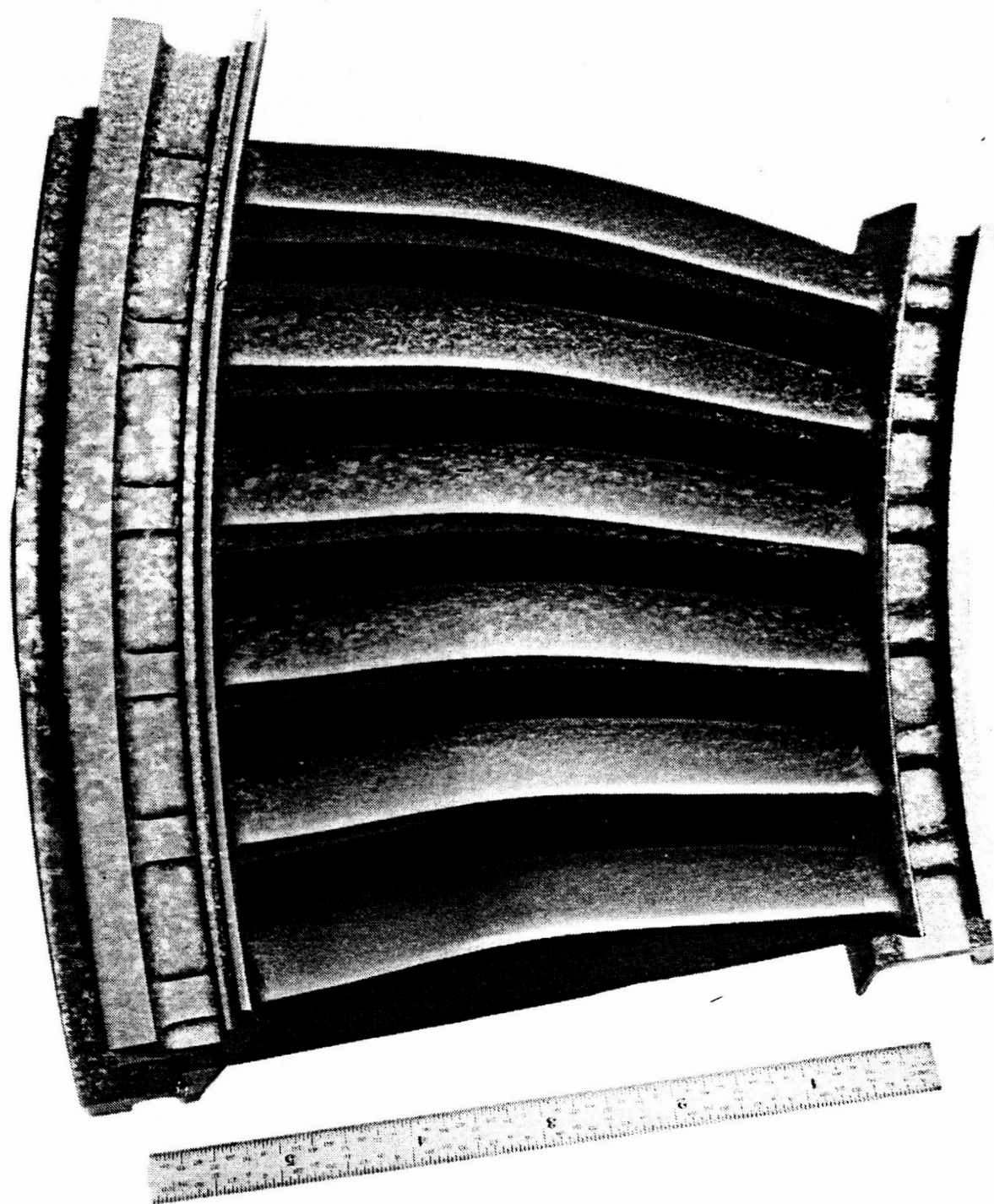


Figure 2.5-9. E<sup>3</sup> Low Pressure Turbine Stage 2 Nozzle Segment - Sample Casting.

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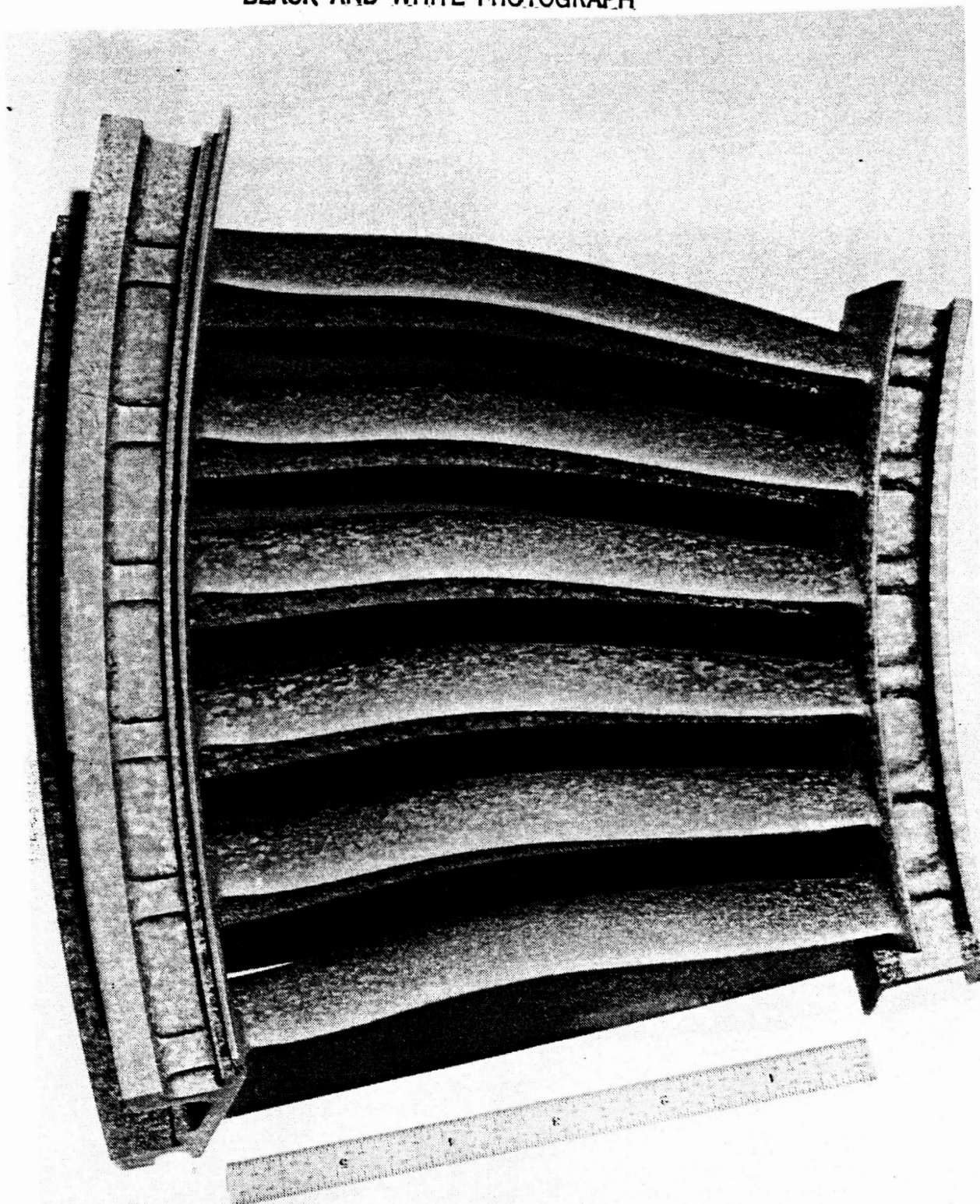


Figure 2.5-10. E<sup>3</sup> Low Pressure Turbine Stage 3 Nozzle Segment - Sample Casting.



Figure 2.5-11. E<sup>3</sup> Low Pressure Turbine Stage 5 Nozzle Segment - Sample Wax Pattern.

### Nozzle Machinings

The order for all four nozzle machinings has been placed at one vendor (Johnson Mold). The long delivery cycle as originally quoted is being negotiated downward. With castings to be delivered in October 1981, machined parts may be ready as early as March 1982, well ahead of the required date for ICLS assembly.

During this period, several vendor-requested changes have been incorporated by DCID. These changes will be reflected in the parts delivered.

Nozzle instrumentation rework planning has progressed to the point where rework drawings can be started. These drawings will be issued in time to incorporate into the machining cycle.

### Work Planned

- Give casting vendor final release to supply balance of castings (spares)
- Provide hardware support through castings, machining, and instrumentation rework
- Issue instrumentation rework drawings

## 2.6 TURBINE FRAME AND MIXER

### Overall Objectives

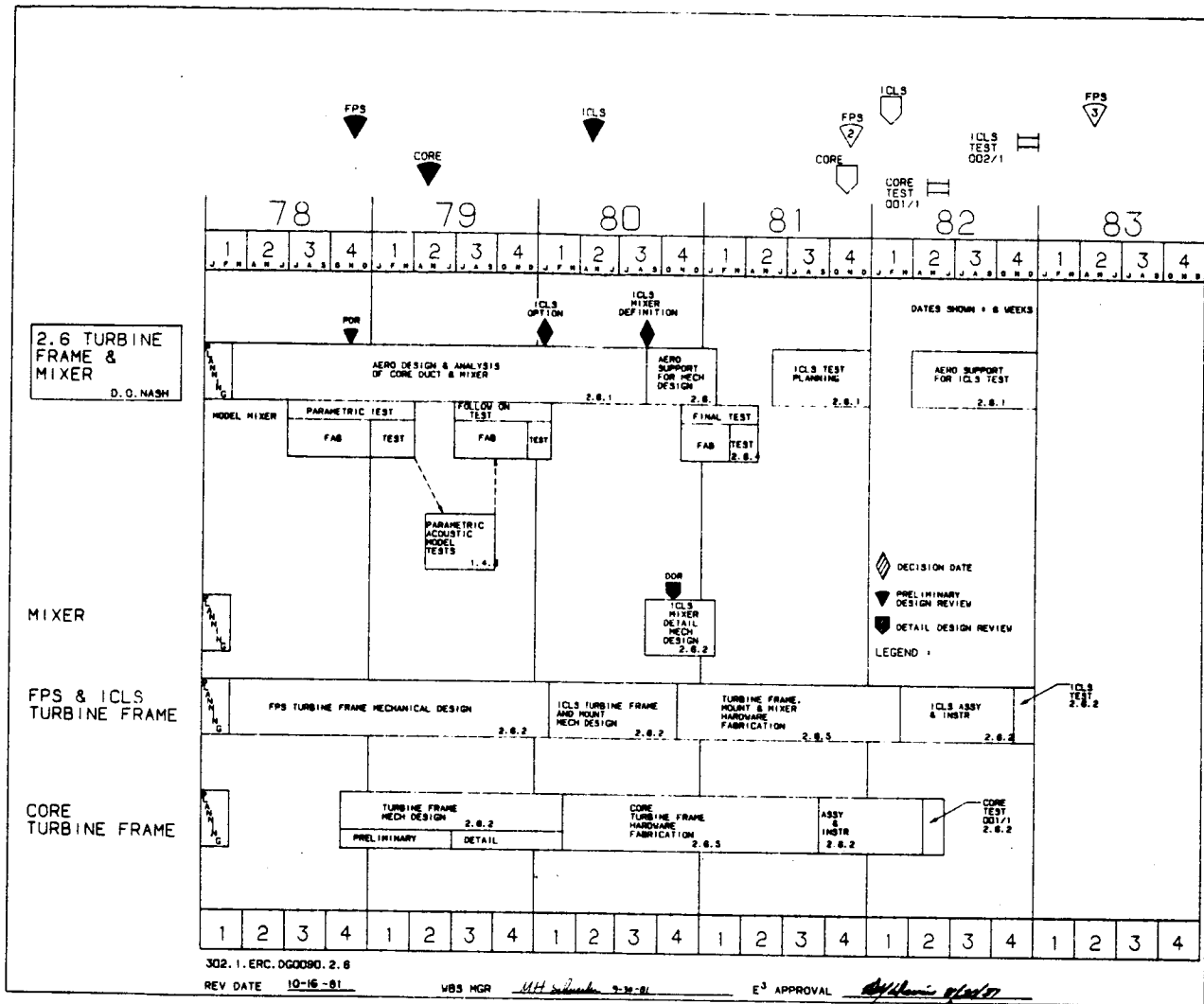
While the E<sup>3</sup> design is based on previous experience with proven engine frames to ensure a long life and maintainable structure, the E<sup>3</sup> frame has been specifically designed with improvements to meet the FPS requirements.

Performance improvements in engines with confluent exhaust nozzles can be achieved by forced mixing of the core and fan flows. A convoluted mixer is planned for the FPS which effectively mixes the hot, high-velocity, core gas with the relatively lower velocity fan air to produce a more uniform velocity at the nozzle throat and improved thermodynamic cycle efficiency. The FPS mixer effectiveness goal is 0.75 at Mach = 0.8, altitude = 35,000 feet, standard day, maximum-cruise power setting.

### Development Approach

Current technology related to the aerodynamic design of high-bypass mixers is not fully developed. Excellent computer techniques are available which allow good aerodynamic flowpath design in terms of low pressure losses with no separation. However, adequate design criteria that provide guidance for selecting a mixer with high mixing effectiveness and low pressure loss does not exist. Thus the first step in the development of a high performance mixer for the E<sup>3</sup> will be to establish a data base from which an advanced technology, high performance mixer, may be designed.

A scale-model mixer parametric test was conducted early in the E<sup>3</sup> program. The models, 12% scale, were tested in a static thrust stand at both cold flow and simulated hot flow conditions. Selected mixer geometric parameters were systematically varied and tested in order to identify those parameters which significantly impact mixing effectiveness. The mixer models selected were consistent with the E<sup>3</sup> thermodynamic cycle and were within practical mechanical and installation constraints. Results of this test identified initial mixing effectiveness and pressure loss design criteria.



Following the parametric test, five of the scale models were evaluated for noise characteristics. Results of the acoustic tests indicated a two-to-four PNdB noise reduction relative to the separate flow exhaust nozzle. Additionally, no discernible difference in noise level for the various mixers tested was observed. Thus noise generation did not effect the selection of the final mixer design.

Results of the mixer parametric test have been used to design and fabricate scale models for a follow-on mixer performance test. This test was aimed at evaluating overall mixer/exhaust system variables with more emphasis on the total  $E^3$  exhaust system. The follow-on test was added to the original program and was intended to provide the design information necessary to achieve an additional 10% mixing effectiveness (75%) relative to the original program goals (65%). Results of the follow-on tests identified significant exhaust system performance characteristics leading to performance improvements and also pointed out the significance of mixer sidewall shape on mixer performance.

Because of the discovery of the significance of mixer sidewall shape on performance in the follow-on test, the verification test was expanded to investigate mixer shape. Additionally, it has been determined that a change to the flowpath in the last several stages of the turbine and turbine frame can improve the mixer performance by an estimated 0.2% sfc at Mach 0.8 maximum cruise. This change was called the flared turbine design, and it was decided that it would be desirable for an FPS design but not timely for the ICLS flowpath. Thus the verification test included a test of a selected best design of the ICLS flowpath based on the previous tests and analytical studies and a continued mixer investigation on the flared turbine FPS flowpath design. The 12-lobe ICLS mixer was tested over a range of operating conditions covering low power SLS to maximum power altitude cruise. Three FPS flared turbine mixers and three additional mixer cutbacks were tested at the cruise condition. Several of the FPS designs met or exceeded the 75% goal mixing effectiveness. One of the FPS mixers was selected for simulated reverse thrust operation testing. Phase III test results are being factored into the ICLS performance predictions and final FPS design selection.

After the successful completion of the mixer verification tests, the detailed mechanical design of the mixer for the ICLS test vehicle was conducted.

This design included an acoustic excitation analysis to establish that no acoustic vibration conditions exist which would result in fatigue life less than the design life of the part. The analysis was carried out by determining the elastic and dynamic characteristics of the panel in question by use of the MASS computer program. These results, together with a damping factor based on the type of construction and the predicted or measured acoustic-pressure levels, were entered into RANDEX, a computer program for predicting the response of structures to random excitation. For RANDEX, the expected root mean square (RMS) cyclic panel stress levels were obtained.

The design of the E<sup>3</sup> turbine frame initially involved preliminary layouts and analysis in order to ensure an adequate radial spring constant. The detail design of the turbine frame involved detailed stress analysis under limiting frame load conditions, such as flight maneuver extremes, rotor imbalance, and transient start-up conditions. Analysis of these load and thermal stress conditions was accomplished by use of the three-dimensional, finite-element computer program, Mechanical Analysis of Space Structures (MASS). By using enough nodes in setting up the analytical model, the elastic behavior and stress levels existing under any combination of loading and thermal stress can be determined. Metal temperature distributions, for use in the MASS analysis, are determined by a transient heat transfer analysis computer program.

The NASA Project Manager has approved the detailed design, and the full-scale turbine frame and mixer are being fabricated. After completion of the manufacture, the hardware will be available for engine assembly.

#### 2.6.1 TRF/M Aero Design

##### Technical Progress

The center vent tube system for the ICLS engine test was simulated in the Phase III scale-model mixer test, WBS 2.6.4. Three vent tube lengths were tested, and the static pressure inside the exit of the tube was measured at simulated maximum SLS power conditions. Test results indicated that the exit pressure will be 5% above ambient pressure for the status vent tube length.

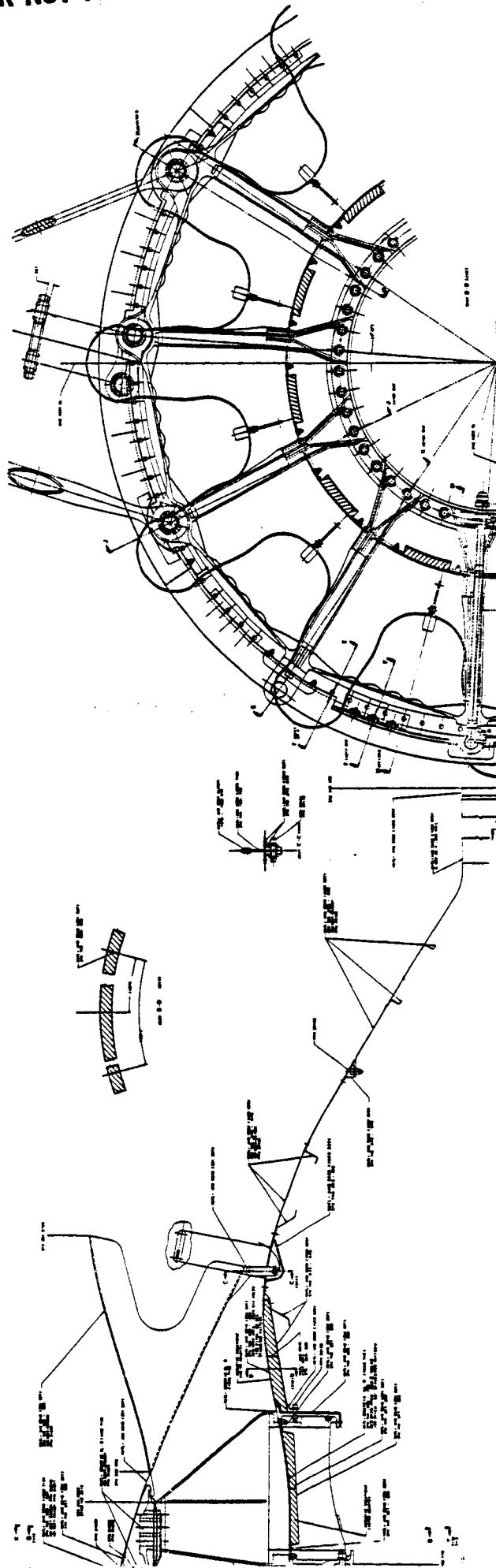


Figure 2.6-1. ICLB Engine Exhaust System Cross Section.

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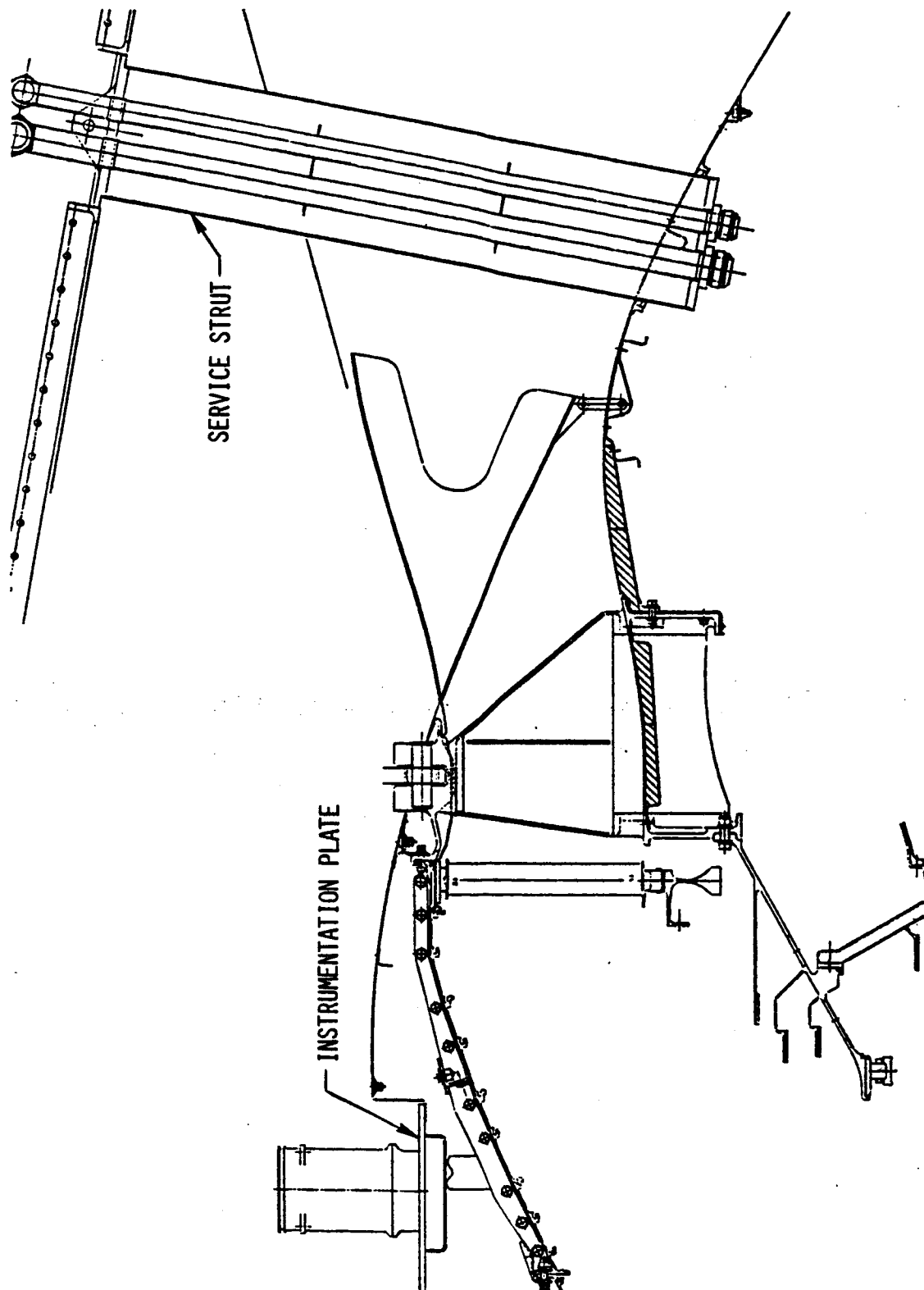


Figure 2.6-2. Turbine Frame and Mixer.

Since the vent system is designed to operate with an ambient exit pressure, the status design would require a change. Analysis of the test results as applied to the ICLS system resulted in a decision to lengthen the vent tube by 12 inches and increase the diameter by 1.5 inches to provide the desired vent tube base pressure and flow area for the estimated vent gas flow.

The WBS replan was completed during this reporting period.

#### Work Planned

Define the FPS mixer design from the scale-model mixer test results, WBS 2.6.4, and provide aero support for the turbine rear frame and mixer as required.

#### 2.6.2 Turbine Frame and Mixer Mechanical Design and Analysis

##### Technical Progress

A cross section of the ICLS engine exhaust system is shown in Figure 2.6-1. No significant design changes have been incorporated into the turbine frame/mixer hardware during the subject reporting period.

The design of the service strut for the aft slipring instrumentation leadout was completed. Figure 2.6-2 shows the location of the service strut. It is located just aft of a cold mixer chute and is pinned to the nozzle at the outboard end and slips into the centerbody at the inboard end. Circumferentially, the service strut is located 75° counterclockwise from top vertical centerline aft looking forward. The strut provides a means for leading out the rotor instrumentation from the aft slipring. Also, the service strut carries freon lines which serve to cool the slipring and a line to provide facility air for seal pressurization.

The natural frequency of the service strut has been calculated to be 572 Hz. This frequency is well above a maximum 1/rev excitation from the fan rotor of 58 Hz. Also considered as a possible excitation source was the strut's vortex shedding frequency. The minimum Karman vortex shedding frequency was determined to be 720 Hz or 26% above the strut natural frequency.

### Work Planned

- Support manufacturing during the continued manufacture of the ICLS hardware.

### 2.6.4 Scaled Mixer Performance Testing

#### Technical Progress

The Phase III 12% scale-model mixer test at FluidDyne was completed in May after 4 weeks of testing. The program included (1) an evaluation of the performance of the selected mixer/exhaust system for the ICLS engine, (2) a continued investigation and development of mixer performance technology for the Flight Propulsion System (FPS), and (3) development of performance and aerodynamic characteristics of the core spoiling system during simulated reverse thrust operation. This test concludes the planned three-phase scale-model mixer program which began in January 1979 to develop the aerodynamic technology needed for the E<sup>3</sup> mixed-flow exhaust system design.

Cross sections and end view of the various mixer configurations are shown in Figures 2.6-3 through 2.6-9. A table identifying several key mixer geometric parameters is presented in Figure 2.6-10.

The final force data has been analyzed to calculate mixing effectiveness and mixer pressure loss for all test configurations. Analysis of the survey data is approximately 50% complete. The survey data has been plotted in several forms and inspected for erroneous readings. The survey data reduction computer program has been modified to handle the specific survey arrangements set up for the Phase III test. Integration of the survey data to determine mixing effectiveness has been initiated.

The mixer configuration selected for ICLS has shown no performance improvement relative to that projected from the Phase II tests. Mixing effectiveness based on the thrust data is 67% with a 0.65% pressure loss giving a 2.05% sfc gain relative to no mixing. It was hoped that a mild degree of twisting of the mixer sidewalls would improve mixing effectiveness; but apparently no gain occurred. Data has been reduced for the ICLS mixer over

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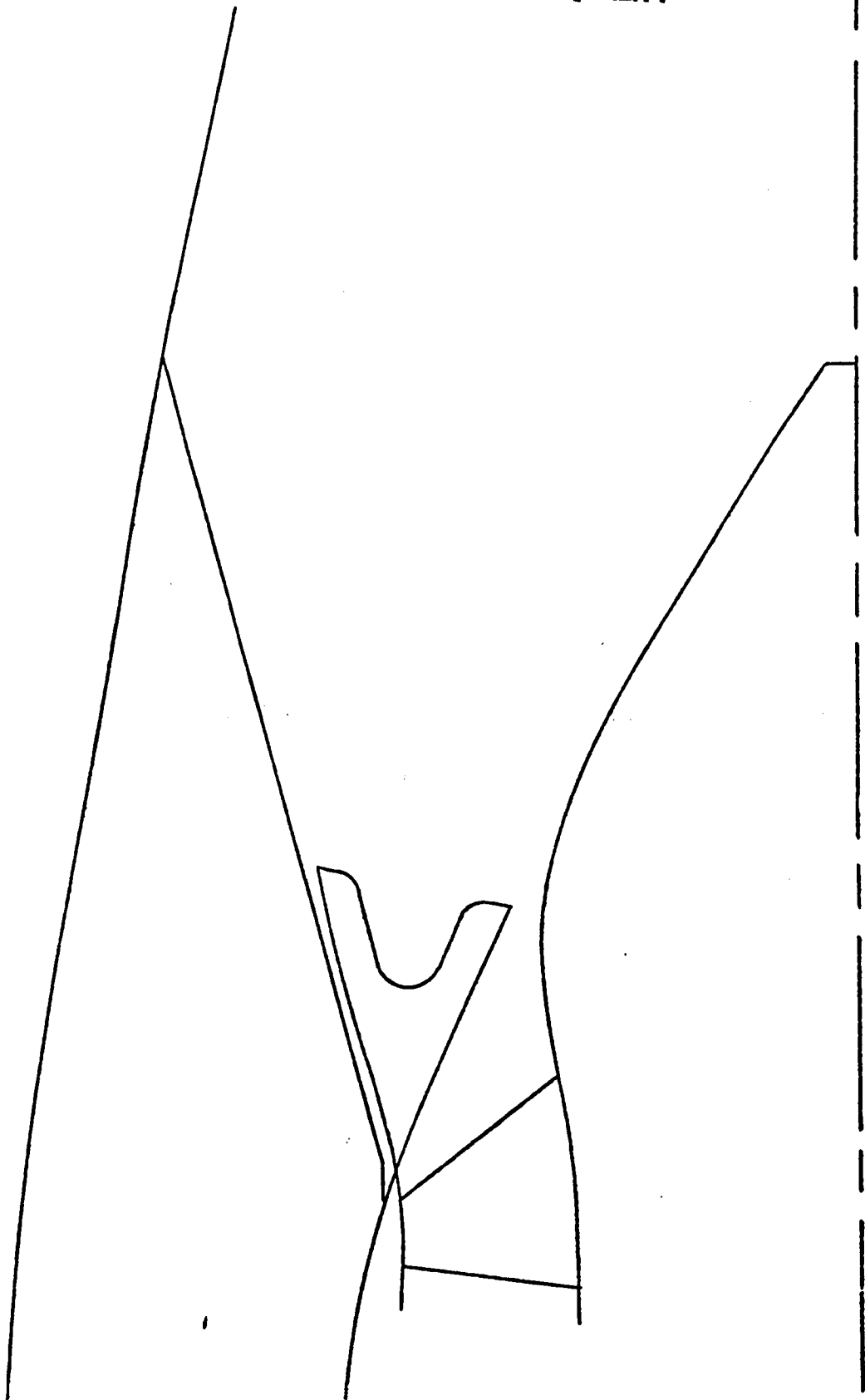


Figure 2.6-3. ICLS Mixer Cross Section, Configuration V2.



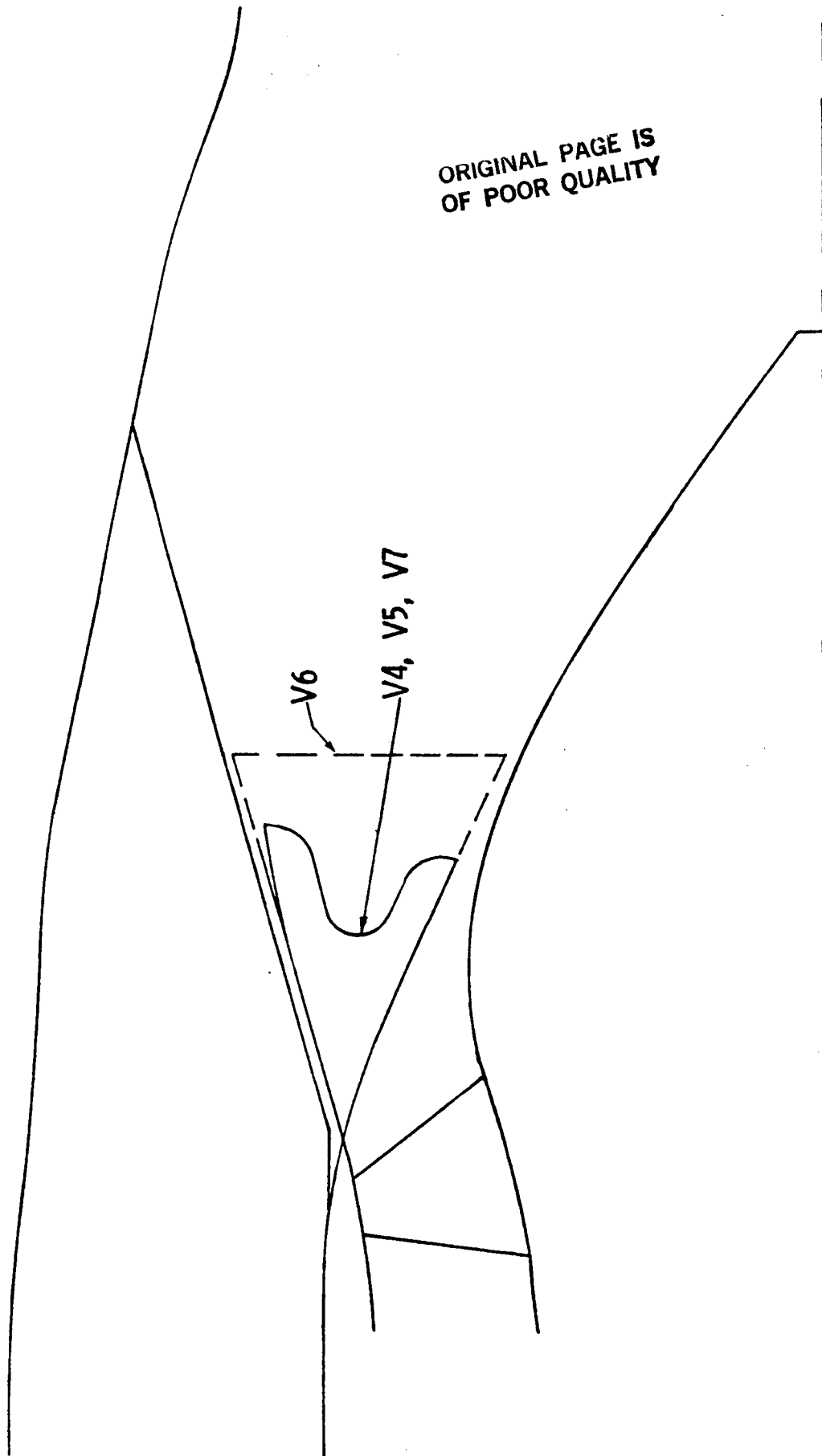


Figure 2.6-5. FPS Mixer Cross Sections.

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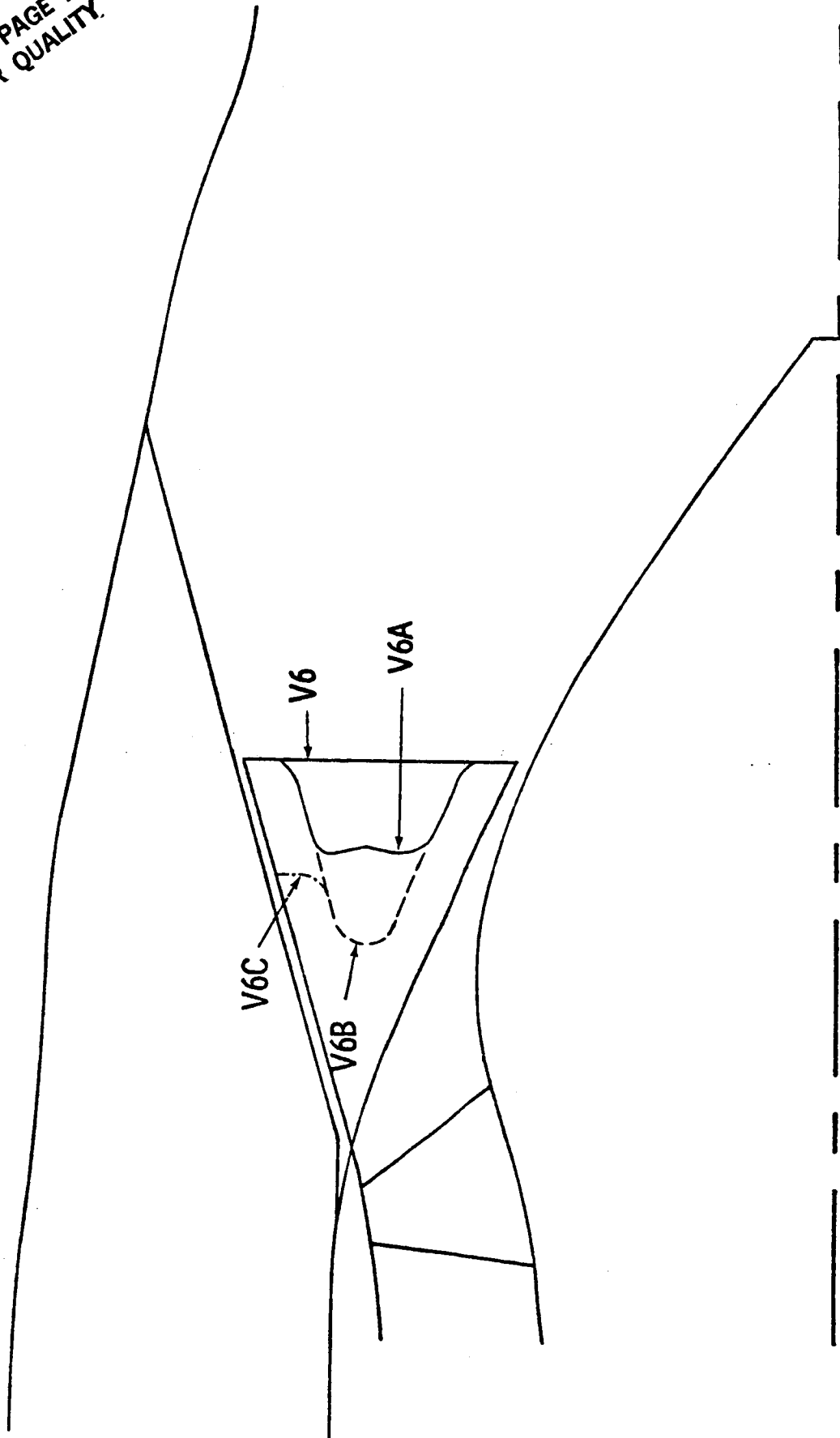


Figure 2.6-6. FPS V6 Mixer Cutbacks.

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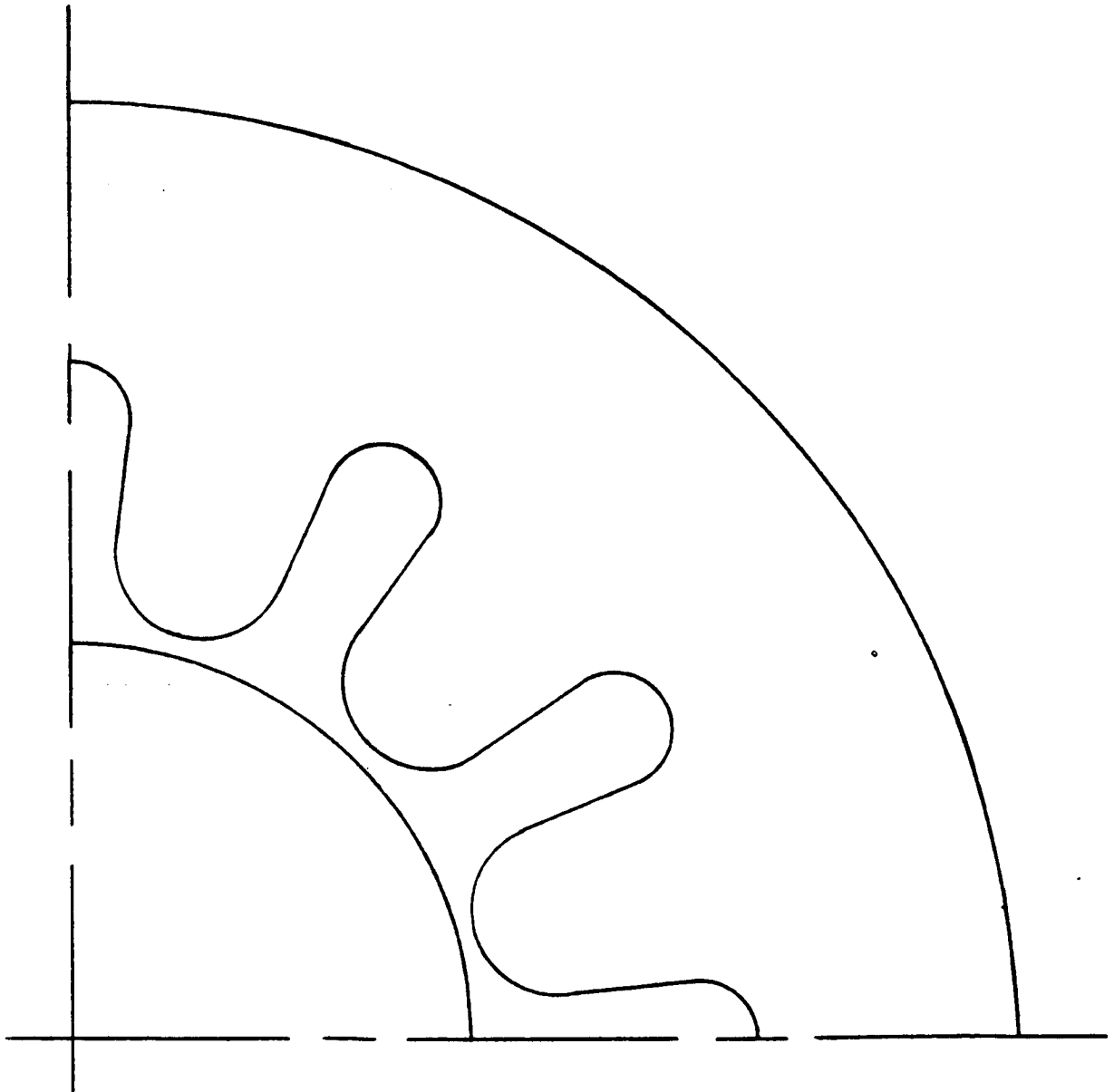


Figure 2.6-7. FPS Mixer V4 End View.

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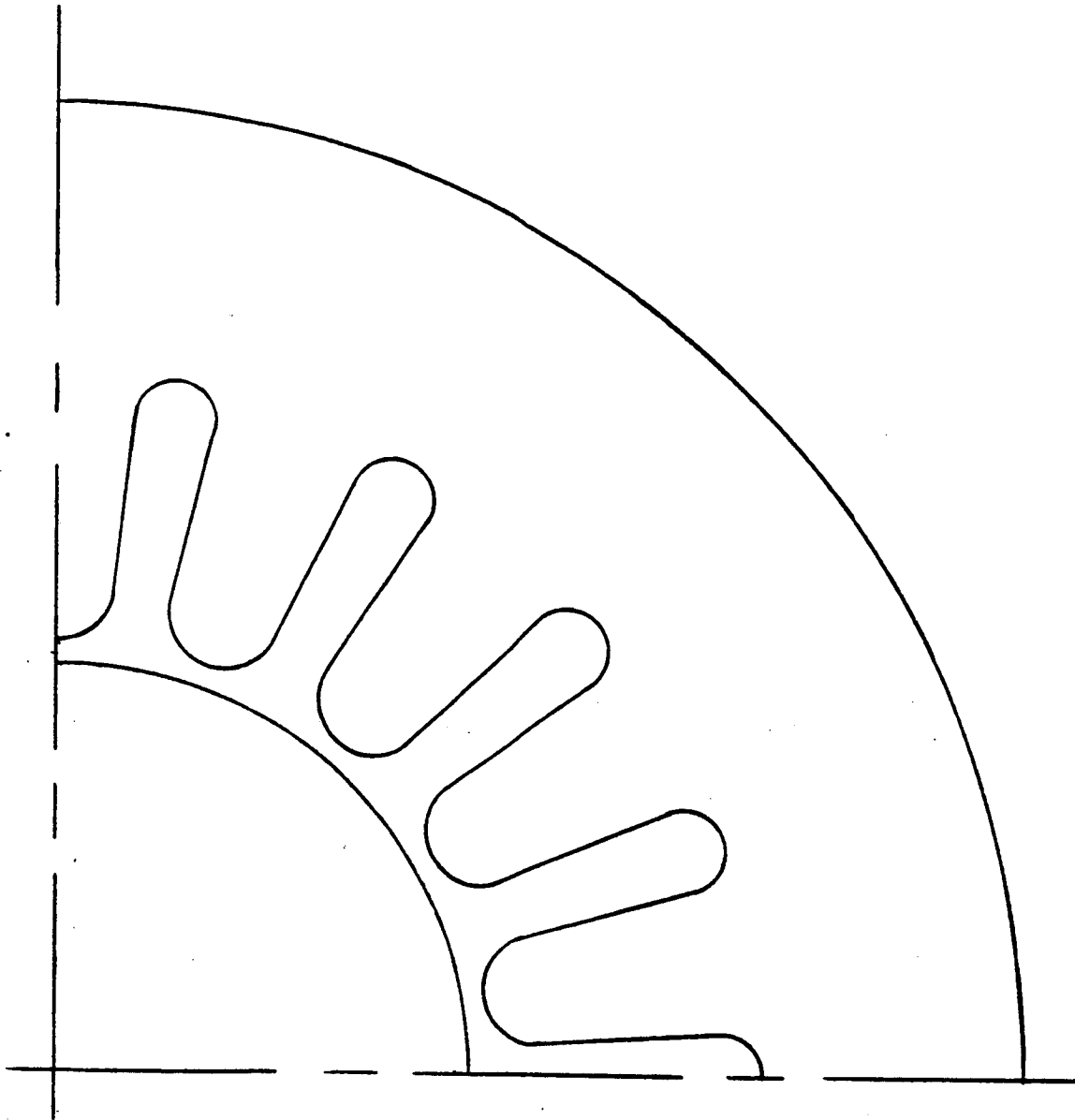


Figure 2.6-8. FPS Mixers V5 and V7 End View.

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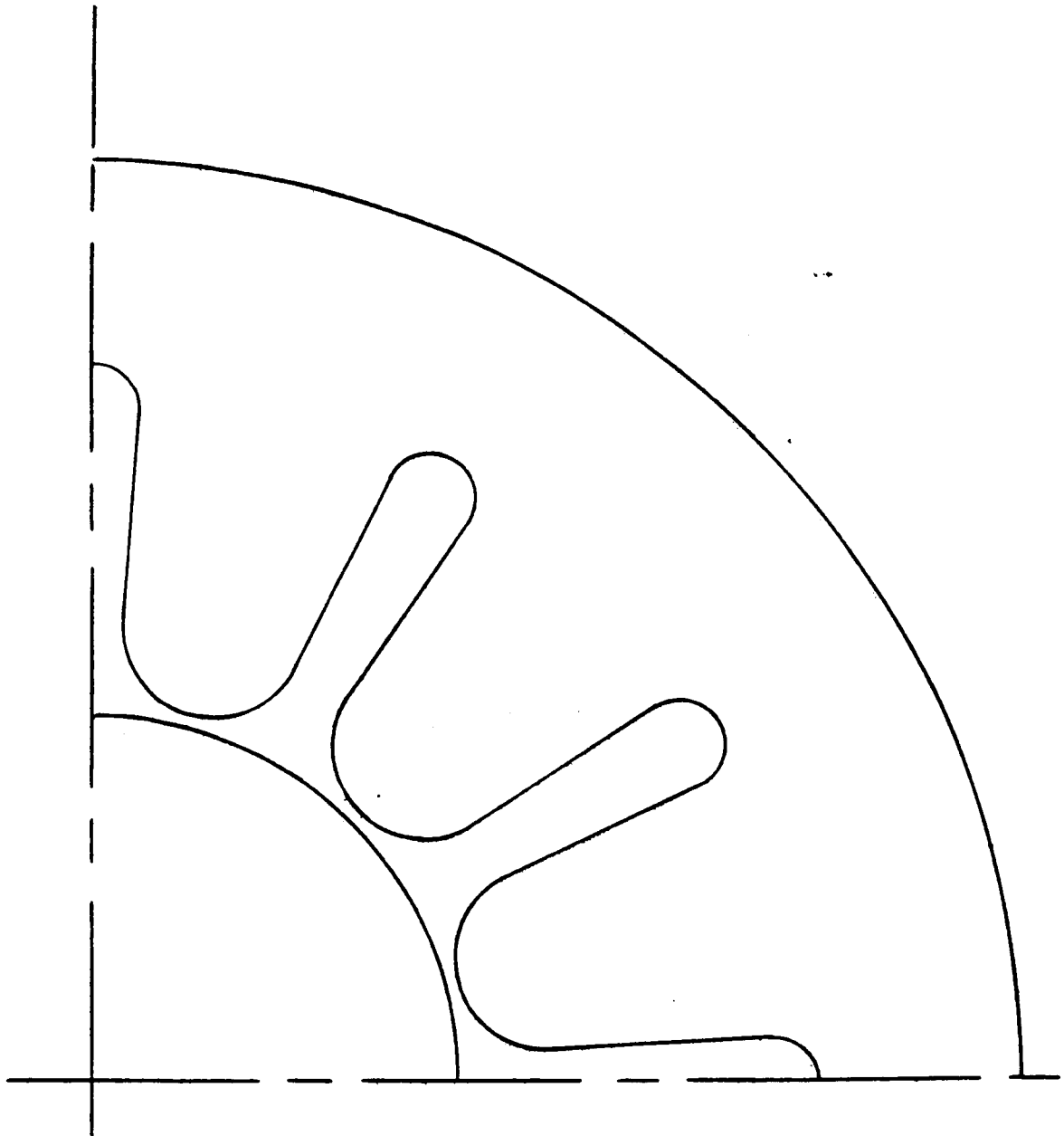


Figure 2.6-9, FPS Mixer V6 End View.

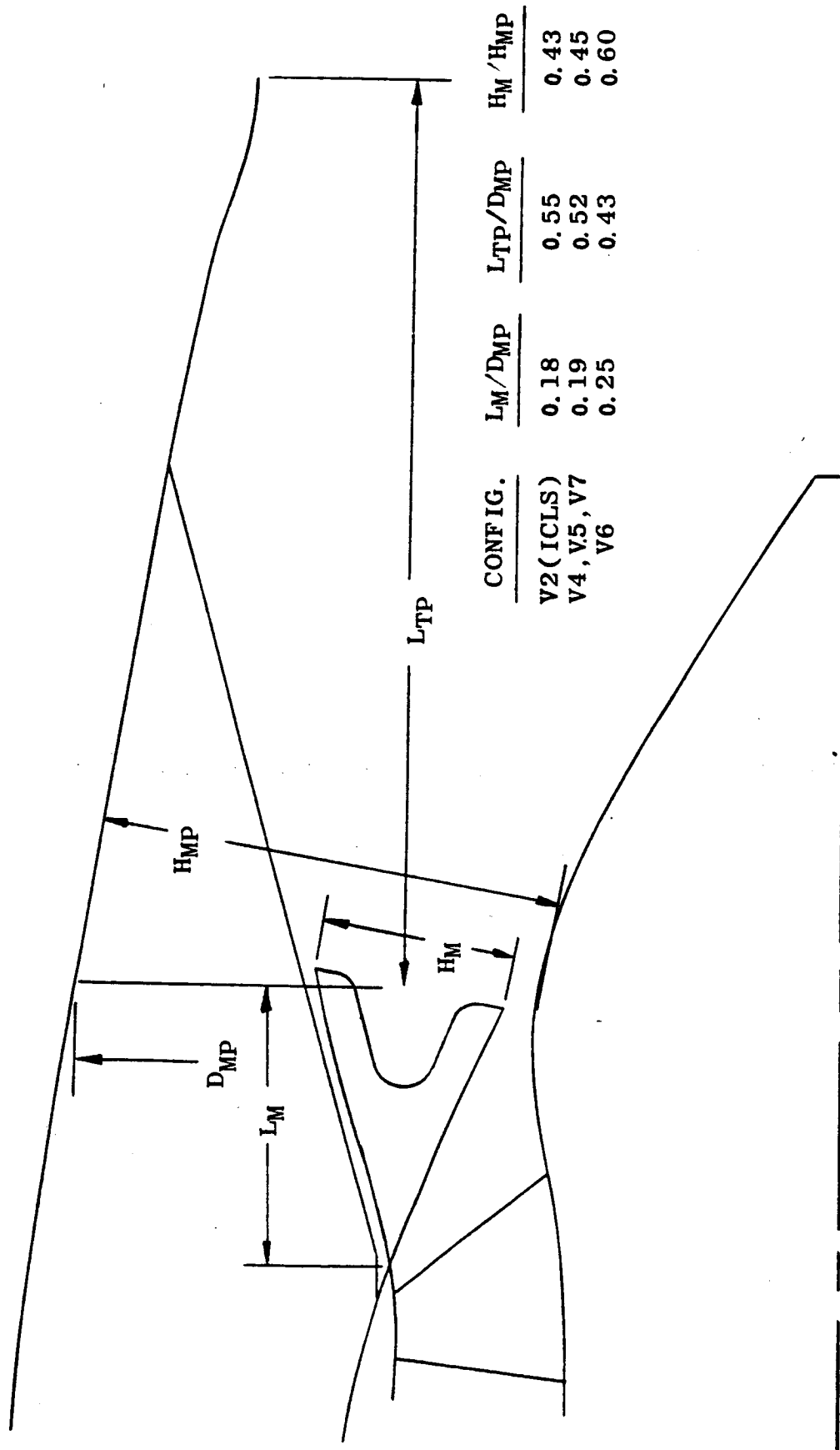


Figure 2.6-10. Mixer and Tailpipe Lengths.

the takeoff and cruise operating region to define the mixing effectiveness and mixer pressure loss. As expected, the pressure loss decreases at the lower takeoff pressure ratios to about 0.4% at the part-power conditions. Mixing effectiveness calculations show considerable data scatter at the takeoff pressure ratios; the mixing values range from 70% to 90%. As concluded from the previous tests, the exit survey data will probably yield a more consistent and reliable mixing effectiveness and will be compared against the full-scale ICLS engine survey results.

Mixing effectiveness and mixer pressure loss results from the FPS configurations were calculated from the final force data. Final results including ICLS, in Figures 2.6-11 and 2.6-12, show the mixer pressure loss ranged from 0.57% to 0.75%, and the mixing effectiveness ranged from 62% to 78%. The best mixer was the 18-lobe V7 design which yielded 78% mixing effectiveness. The corresponding sfc gains at Mach 0.8/35,000 feet maximum cruise are summarized in Figure 2.6-13 for all test configurations. This gain is the improvement relative to no mixing and includes the pressure loss of the mixer and the mixing gain. The ICLS mixer gain is ~2%, and it is clear from this chart that the 18-lobe FPS mixers resulted in the best net sfc gain, 2.6%.

Nozzle exit flow and velocity coefficients for both the ICLS and FPS nozzles have been calculated and were provided to E<sup>3</sup> Systems Performance for incorporation into the cycle decks. A trade study will be performed for the FPS nozzle design to determine an optimum combination of nozzle velocity and flow coefficient characteristics for best overall engine system performance.

Simulated reverse thrust operation data was obtained for the FPS mixer, V4. Results will provide the core system thrust coefficient, fan duct/nozzle cavity pressure level characteristics needed for engine cycle matching, and nacelle aerodynamic heating characteristics to determine FPS reverser leakage and bleed flow needed to maintain nacelle temperatures below material limits.

The WBS replan was completed during this reporting period.

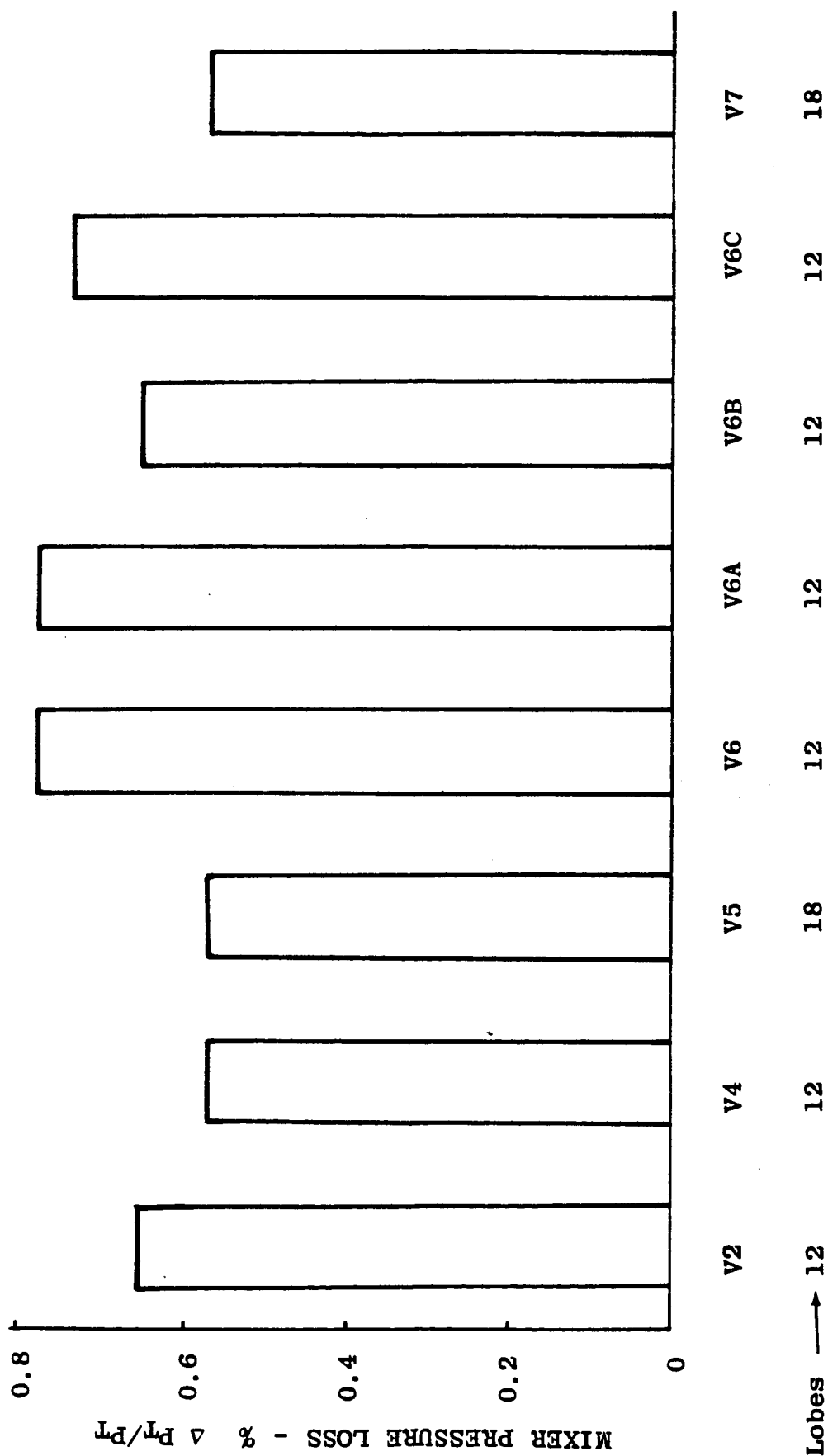


Figure 2.6-11. Mixer Pressure Loss Summary.

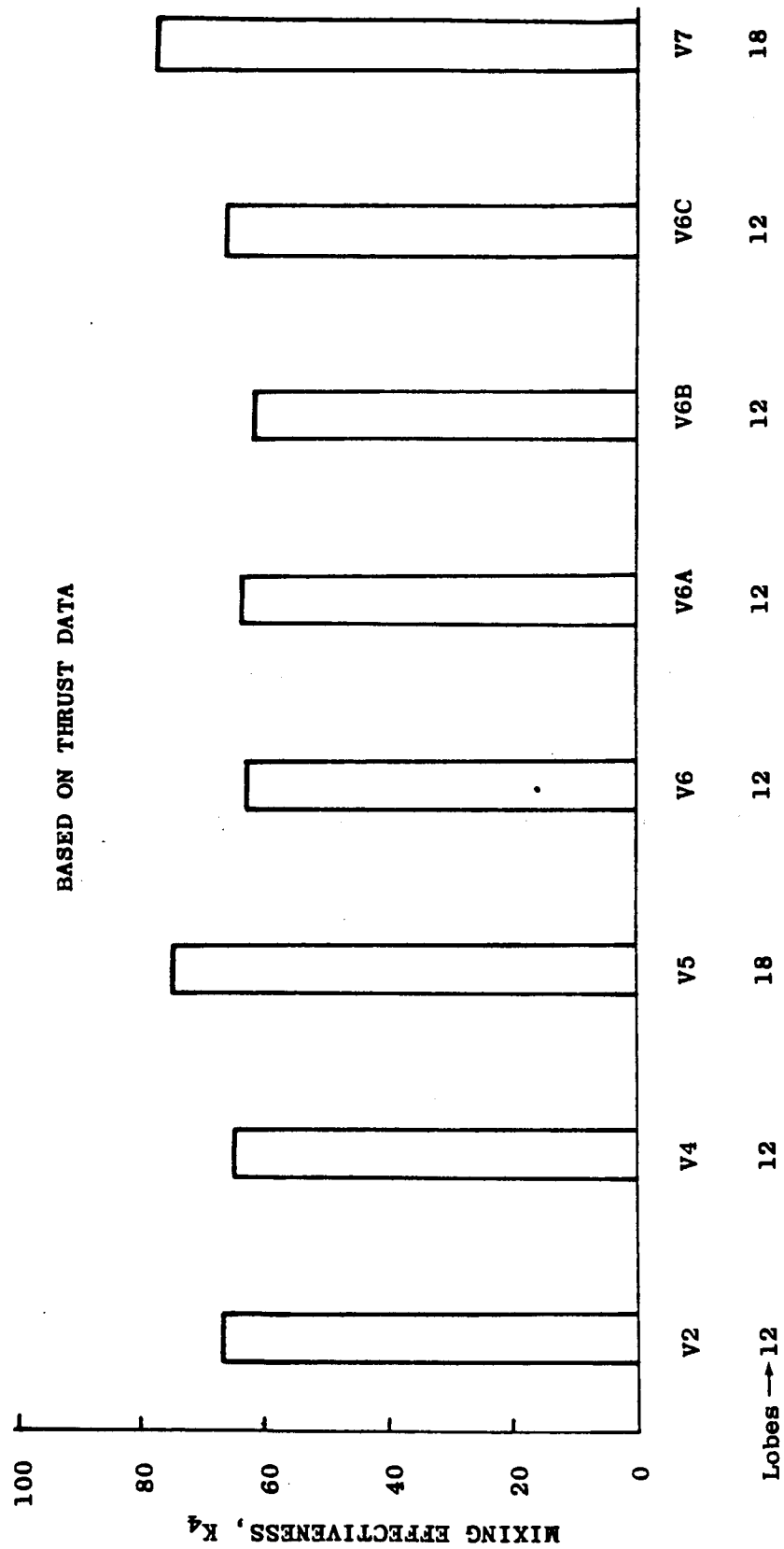


Figure 2.6-12. Mixing Effectiveness Summary.

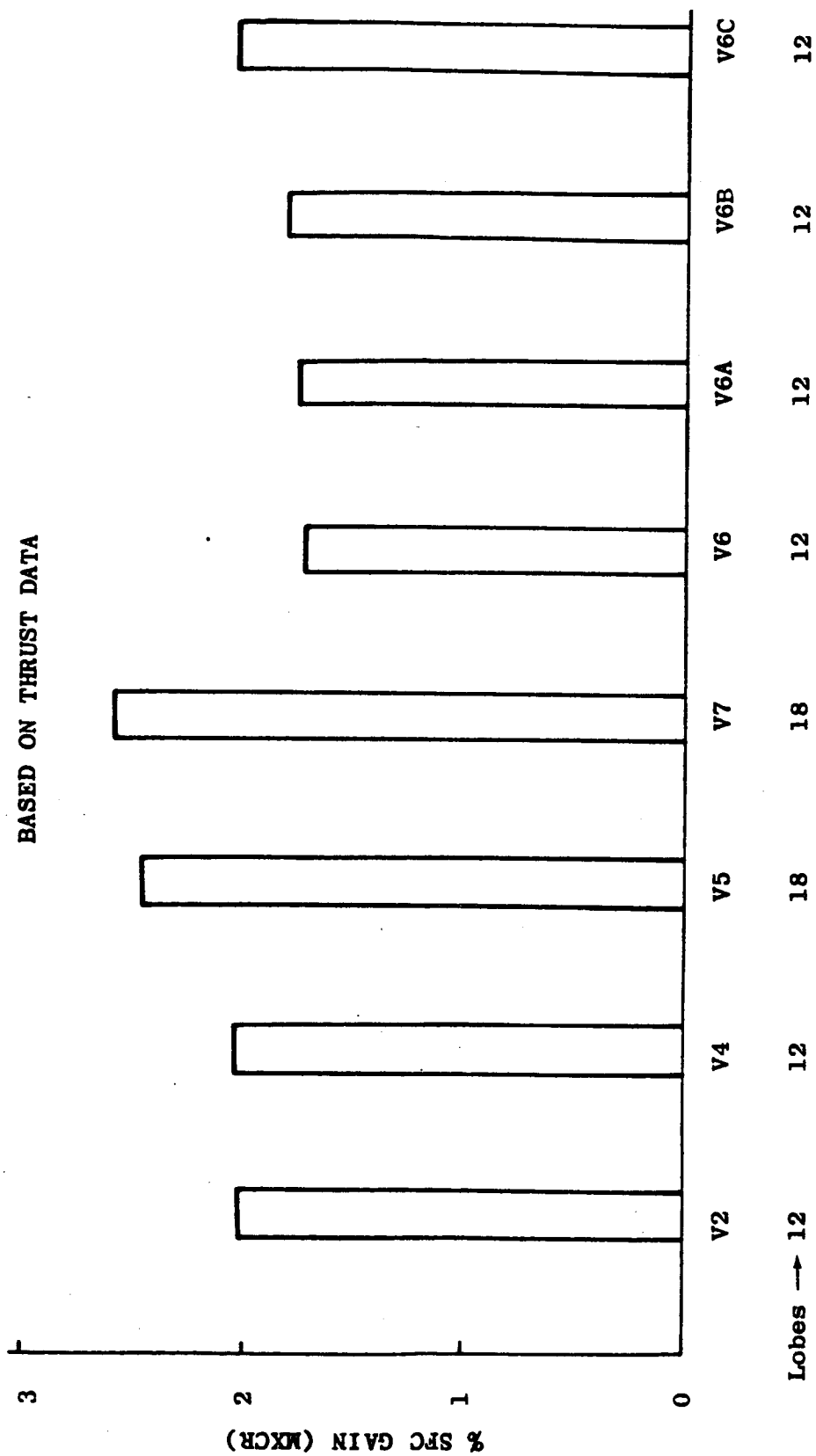


Figure 2.6-13. SFC Gain Summary.

### Work Planned

Complete the analysis of the Phase III test results and prepare a formal report for the entire three-phase test program.

#### 2.6.5 Turbine Frame/Mixer Fabrication

##### Technical Progress

##### Core Engine Exhaust System

A cross section of the core engine exhaust system is shown in Figure 2.6-14. All core engine exhaust system hardware is complete except the stationary seal support. This seal will be completed by the end of October and will be in-house well before it is necessary for the engine assembly cycle.

Figure 2.6-15 is a photograph of the slave turbine frame for the core engine. The rear engine mount and one of the two symmetrically positioned ground handling lugs can be seen in the photograph. Also shown are the fittings on the outboard end of the struts which supply the shop air for cooling the frame (quantity: four) and which route the fifth stage bleed air through the frame to pressurize the second stage high pressure turbine aft cavity (quantity: four). The convection cooling baffle in the hub of the frame can be seen in Figure 2.6-15 also. This baffle has had some doublers added to provide sufficient structural integrity under the most adverse pressure loading condition which could be possible in the planned test.

##### ICLS Engine Exhaust System

Considerable progress has been made on the ICLS exhaust system hardware during the subject reporting period. All components which make up the turbine rear frame have been completed. These include the strut ends, the casing polygonal panels, the strut halves, the strut end extensions, the hub rings, and the hub shear cylinder. The strut ends and the polygonal panels are currently being welded together to form the frame outer casing. The tooling

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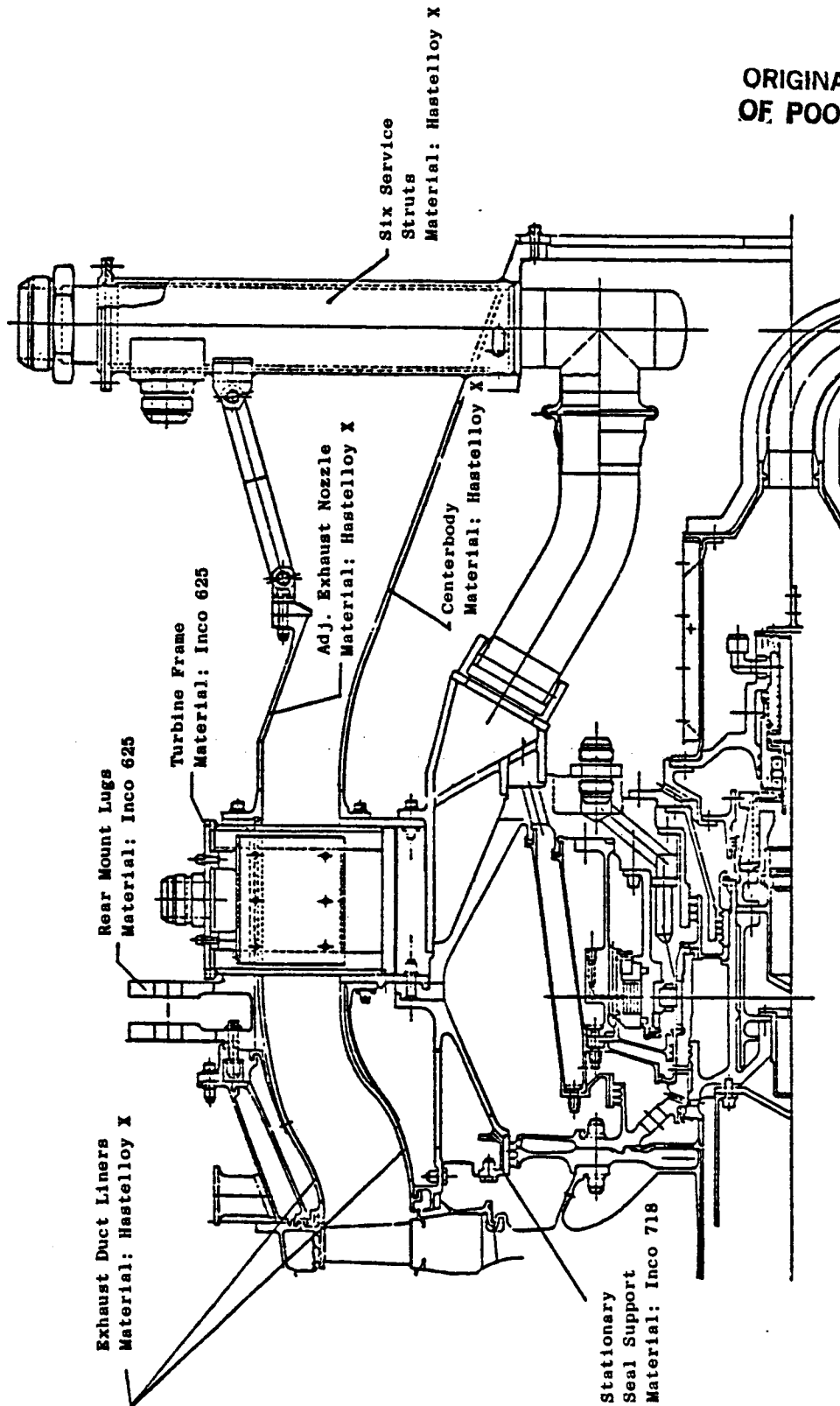


Figure 2.6-14. Core Engine Exhaust System Cross Section.

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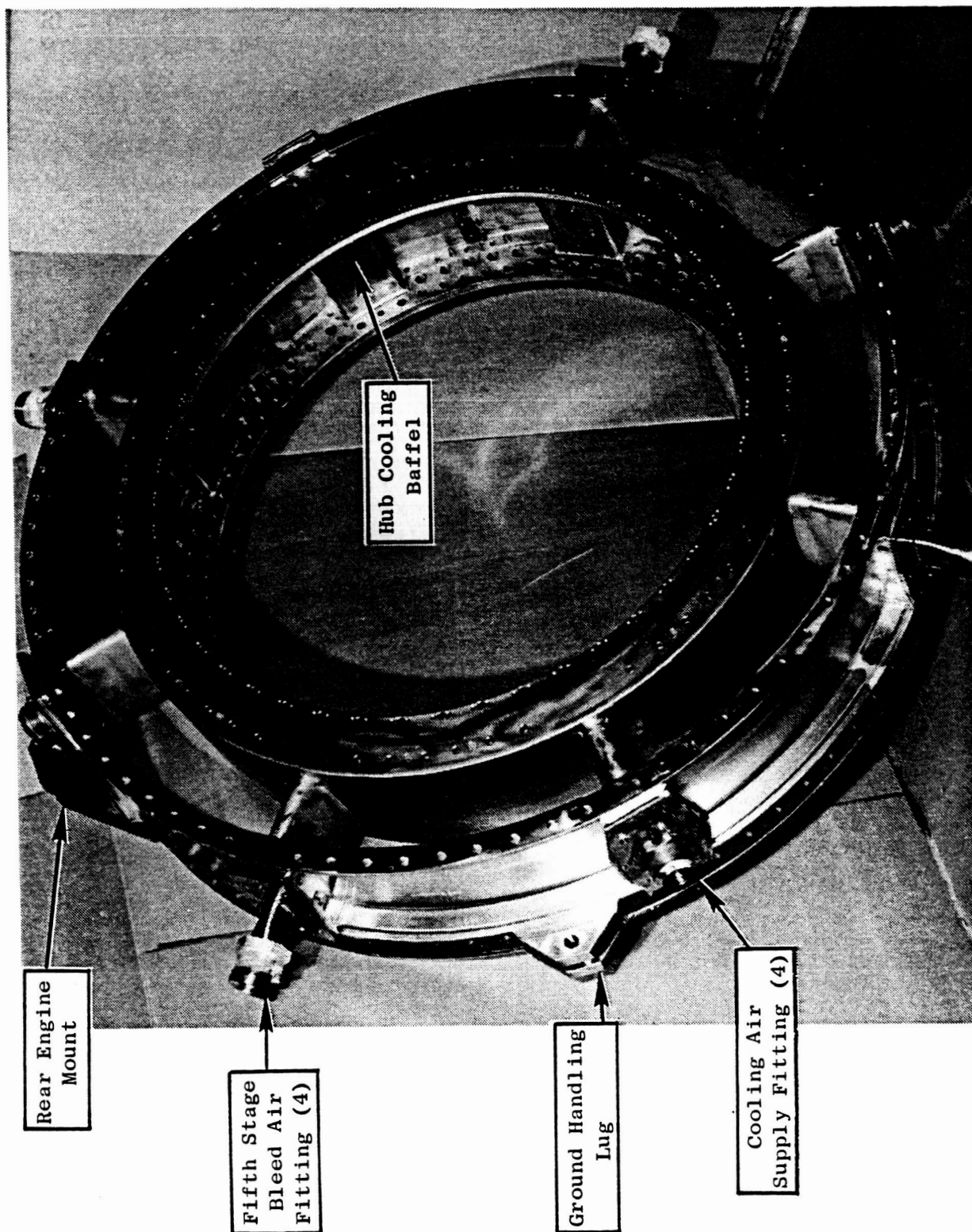


Figure 2.6-15. Core Engine Turbine Frame.

required to size the casing after all welding takes place has been completed also. The frame casing liner, formed at an outside vendor, has been completed and is in-house.

The spinnings required for the aft inner core cowl, the forward centerbody, and the aft centerbody have been completed. Fabrication of the tooling necessary for forming the mixer chutes has been initiated.

#### Work Planned

- Complete fabrication of stationary seal for core engine
- Complete ICLS turbine frame manufacture
- Continue fabrication of ICLS aft inner core cowl, mixer, and centerbody.

## 2.7 BEARINGS, SYSTEMS, DRIVES, AND CONFIGURATIONS

### Overall Objectives

Bearings, systems, drives, and configuration components encompass the following:

- Main shaft support bearing and seal components
- Accessory drive system
- Lube system, including rotor thrust balance
- External piping and wiring configuration of the engine.

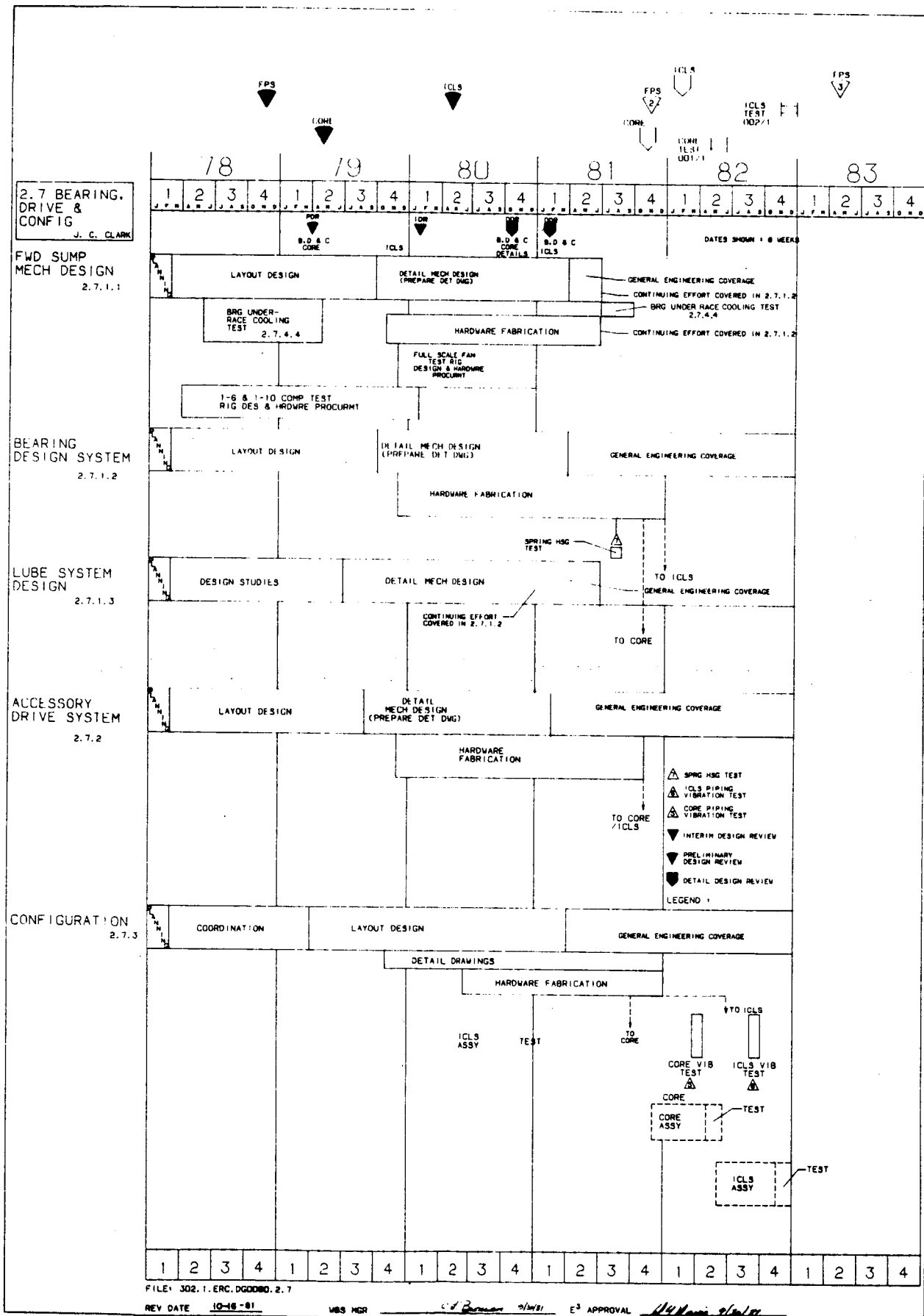
The main shaft bearings will be designed to properly support the engine rotor systems. These bearings will meet the design requirement for engine life considering fatigue and skidding criteria. They will operate with minimum heat rejection and within specified limitations.

The accessory drive system will provide the means to drive the engine-required accessories. Adequate horsepower capability, the proper pad speeds, and direction of rotation are the primary design objectives. Provision for two starter pads will be provided on the Core/ICLS accessory gearbox. Critical speeds of all gearbox shafting will be kept at least 20% above the engine operating speed. The internal configuration of the accessory gearbox will be designed so that lubricating and cooling oil will be easily scavenged from it. During engine operation, the gearbox will operate within specified temperature limits.

The lube system will be designed to provide a flow network that will deliver and remove specific amounts of oil from various areas of the engine while maintaining predetermined pressure drops in the individual circuits. The rotor thrust balance will be determined as part of the lube system activity, and the thrust load on the fan and core thrust bearings will be established to be compatible with the life requirements of the bearings.

The objective of the configuration design is to provide the required external wiring and piping between various components of the engine. Piping is sized to meet specified flow velocities. The piping and wiring array will be capable of operating in the temperature and vibration environment of the engine.

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### Development Approach

To achieve the foregoing objectives, a development program has been established that consists of five subprograms defined as follows:

- Forward Sump Mechanical Design (WBS 2.7.1.1)
- Aft Sump Design (WBS 2.7.1.2)
- Lube System Design (WBS 2.7.1.3)
- Accessory Drive system (WBS 2.7.2)
- Configuration (WBS 2.7.3)

The major layout design of the forward and aft sumps was accomplished during 1978 through the third quarter of 1979. Preliminary design work was aimed at obtaining a viable design for the Flight Propulsion System. Studies have been made integrating the sumps with the core (high pressure) and low-spool (low pressure) rotor systems. Bearing and support housing designs are being analyzed in terms of rotor speeds, loads (including blade-out), cost, weight, and maintainability.

During the replanning activity of June 1981, Subprograms 2.7.1.1 and 2.7.1.3 were combined into Subprogram plan 2.7.1.2. This consolidation was made because the major design and analysis work has been completed and reporting will be more efficient.

The Core PDR was held in the second quarter of 1979, and an Integrated Core/Low Spool IDR was held in the third quarter of 1979. With NASA approval, the detail mechanical design was initiated with planned completion in the fourth quarter of 1980. With the exception of the configuration drawings, all design drawings were issued the first quarter of 1981. The Core and ICLS bearing and sumps DDR were held in the fourth quarter of 1980 and the second quarter of 1981, respectively. The ICLS bearings and sumps IDR was held in the first quarter of 1980.

Following NASA approval, hardware procurement and fabrication proceeded.

Two bearing tests have been planned to establish lubrication methods, provide heat-rejection data, and establish other design parameters for the

Core thrust bearing and the intershaft bearing. The thrust-bearing underrace cooling test (WBS 2.7.7.4) will be completed in two phases. The first phase was completed during the second quarter of 1979, and the second phase (which will test an E<sup>3</sup> core thrust bearing) will be completed in the third quarter of 1981. The intershaft bearing test simulating the aft intershaft bearing arrangement of the E<sup>3</sup> design (WBS 2.7.4.3) scheduled to run in the fourth quarter of 1979, was run in the first quarter of 1980. During the replan of June 1981, further testing under this WBS was terminated. Bearing IRC will be determined by analytical means.

The lube system preliminary and detail design efforts supports the mechanical design work in such areas as lube system network, main shaft seal-pressurization networks, and rotor thrust. The PDR for the lube system was scheduled and completed as part of the Core and ICLS PDR's. During the detailed mechanical and design effort, the lube system activity concentrated on finalizing such parameters as (1) lube flow and pressures, (2) seal  $\Delta P$ 's at various operating conditions, and (3) updating the rotor thrust-balance status.

While preliminary mechanical studies were continuing on the sump systems, a parallel work effort went on in the accessory drive area. The design effort was in support of the FPS being designed under the Task I effort. The effort was centered on the power takeoff (PTO), accessory gearbox (AGB), and the connecting shafting. The PDR for the accessory drive system was scheduled and completed as part of the Core PDR. Detail design work has now been completed for the Core/ICLS engine.

During 1978 and running through the first quarter of 1979, the configuration effort was concentrated on coordination with all the interfacing units and design layouts of all external wiring and piping. All detailing will be completed by the fourth quarter of 1981. Vibration tests were also planned as a supporting effort for the scheduled Core and ICLS tests.

In addition to the aforementioned effort, design and procurement of specific test rig hardware has been provided in support of the 1-6 and 1-10 compressor tests and the full-scale fan test (FSFT).

### 2.7.1.1 Forward Sump Mechanical Design

#### Technical Progress

During this reporting period, design effort has been applied in the following areas:

- FSFT forward sump
- 1-10 compressor rig forward sump
- Core engine forward sump design
- Forward sump for ICLS engine.

As specified in the "Overall Objectives," this WBS has been incorporated into WBS 2.7.1.2 and future reporting on the forward sump will be in that WBS.

#### FSFT Forward Sump

The FSFT forward sump configuration is shown in Figure 2.7-1. The design is described in Semiannual Report No. 5 and all hardware has now been assembled and is awaiting test.

During assembly into the rig, the tie bolt threads became seized in the facility drive shaft. The end of the bolt had to be removed by cutting, and an adapter piece was made to fit drive shaft threads. This has been completed and setup was completed.

#### 1-10 Compressor Rig Forward Sump

At the disassembly of the first build of the 1-10 compressor rig, an oil leak was noticed in the forward sump area. An additional O-ring has been added to the forward cover plate as a backup to seals around individual oil ports.

Strain gages have also been added to the spring beams to help in the vibration monitoring during operation. Strain gages have been mounted and checked out and housing is ready for assembly.

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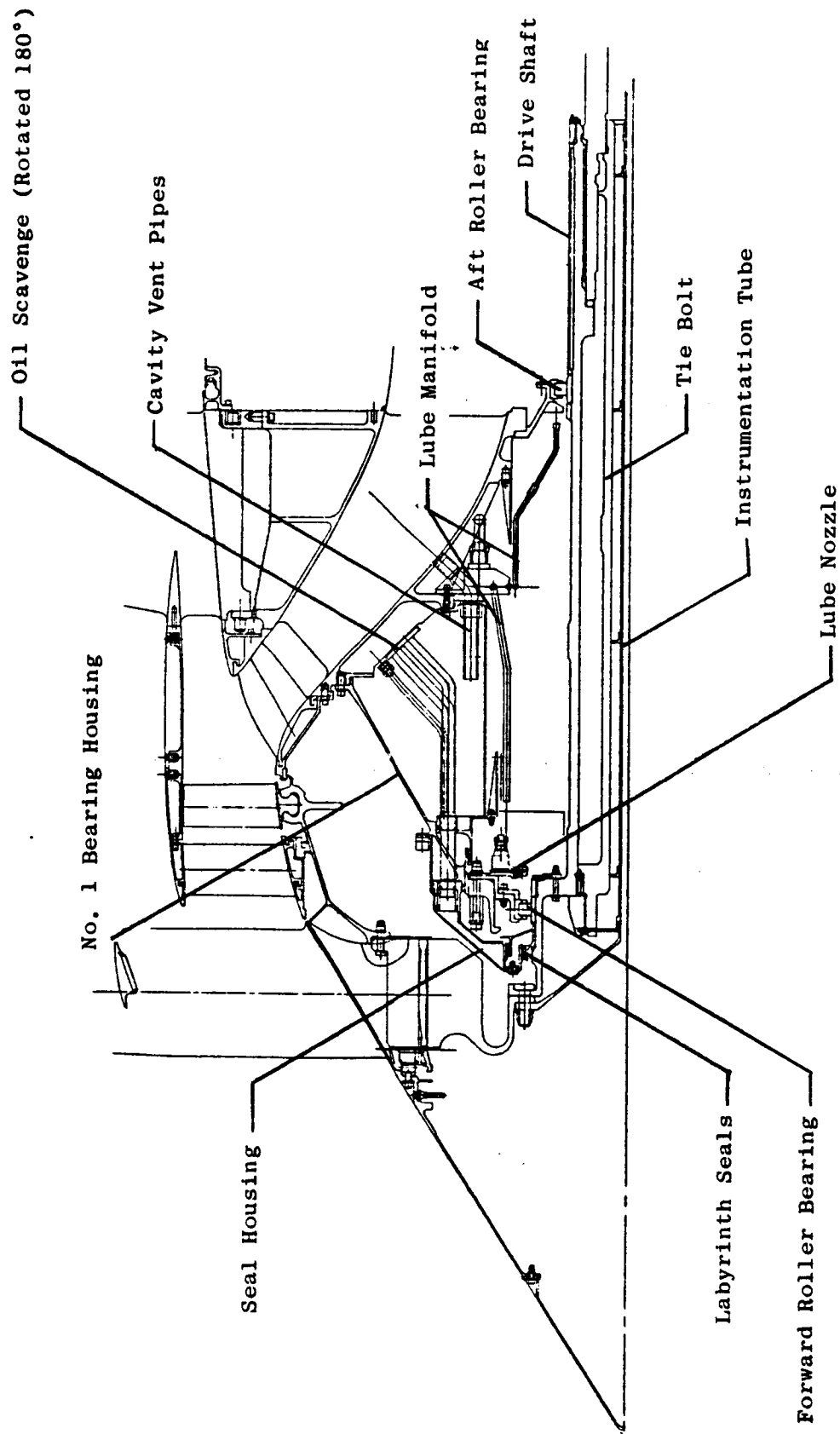


Figure 2.7-1. Forward Sump for Full Scale Fan Test.

### Core Forward Sump Design

The Core forward sump is shown in Figure 2.7-2. The design is the same as reported in Semiannual Report No. 4 and detail drawings have been completed and hardware is in the manufacturing cycle.

Major emphasis has been on engineering support during the manufacturing cycle and during assembly planning.

### Forward Sump for ICLS Engine

The ICLS forward sump is shown in Figure 2.7-3. Semiannual Reports No. 4 and 5 describe design features of this sump. The design incorporates hardware that is common with the FSFT and will be tested first during the fan test.

Major emphasis during this reporting period has been engineering support during the manufacturing cycle.

### Work Planned

- Continue procurement of hardware for the Core and ICLS engine
- Provide engineering coverage during second build of 1-10 compressor rig
- Provide engineering coverage during mechanical checkout of FSFT.

### 2.7.1.2 Aft Sump Mechanical Design

#### Technical Progress

During this reporting period, design effort has continued in the following areas:

- Aft sump for the Core engine
- Aft sump for the ICLS engine
- ICLS LPT shaft design.

The scope of this WBS has been expanded to include WBS 2.7.1.1 and 2.7.1.3 as specified in the "Overall Objectives," and reporting for the next semiannual report will reflect this.

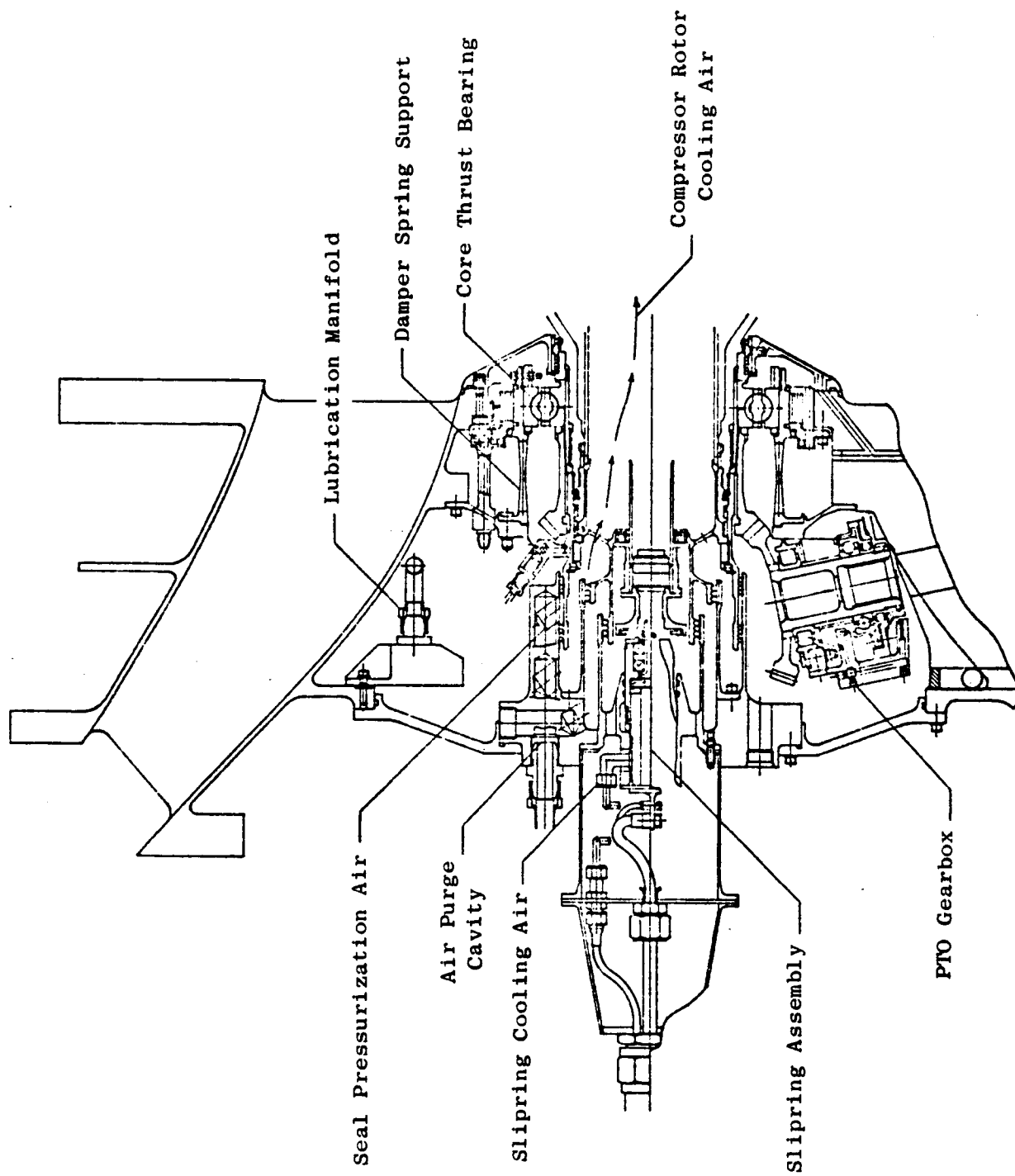


Figure 2.7-2. Core Forward Sump.

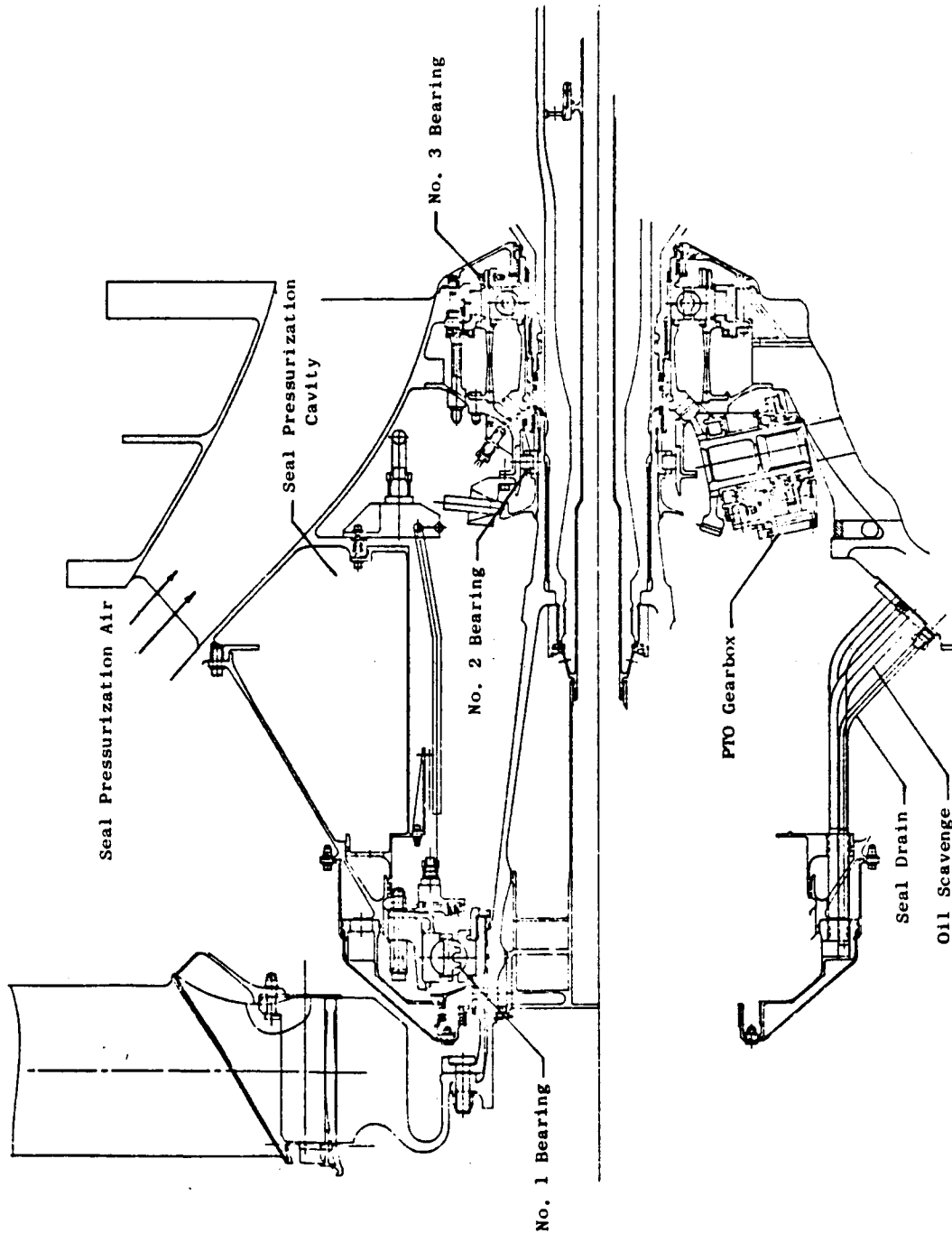


Figure 2.7-3. ICLS Forward Sump.

#### Aft Sump for the Core Engine

The Core engine aft sump is shown in Figure 2.7-4. All hardware is in the manufacturing cycle. Some minor manufacturing discrepancies have required recalculation of the beam stiffness of the bearing centering spring. Recalculations indicate beams will be acceptable for the Core engine.

Some minor modifications will be required to sump hardware due to incorporation of a 200 rather than a 100 point instrumentation slipring. Rework is presently being defined.

Engineering coverage will continue during the manufacturing process.

#### Aft Sump for the ICLS Engine

The aft sump for the ICLS engine is shown in Figure 2.7-5. All drawings have been completed and hardware is in the manufacturing cycle.

Engineering coverage is continuing during the manufacturing process.

#### ICLS LPT Shaft Design

The detail drawing for the LPT Shaft has been issued and a manufacturer has been selected. Because of the complexity of the part, an engineering review at the vendor's plant has been held to review the design intent and manufacturing processes.

Some minor modifications are being made to the air seals and these changes are in process.

#### Work Planned

- Continue engineering coverage during manufacturing process.

#### 2.7.1.3 Lube System Design

#### Technical Progress

During this reporting period, work has been done for both the Core and ICLS engine.

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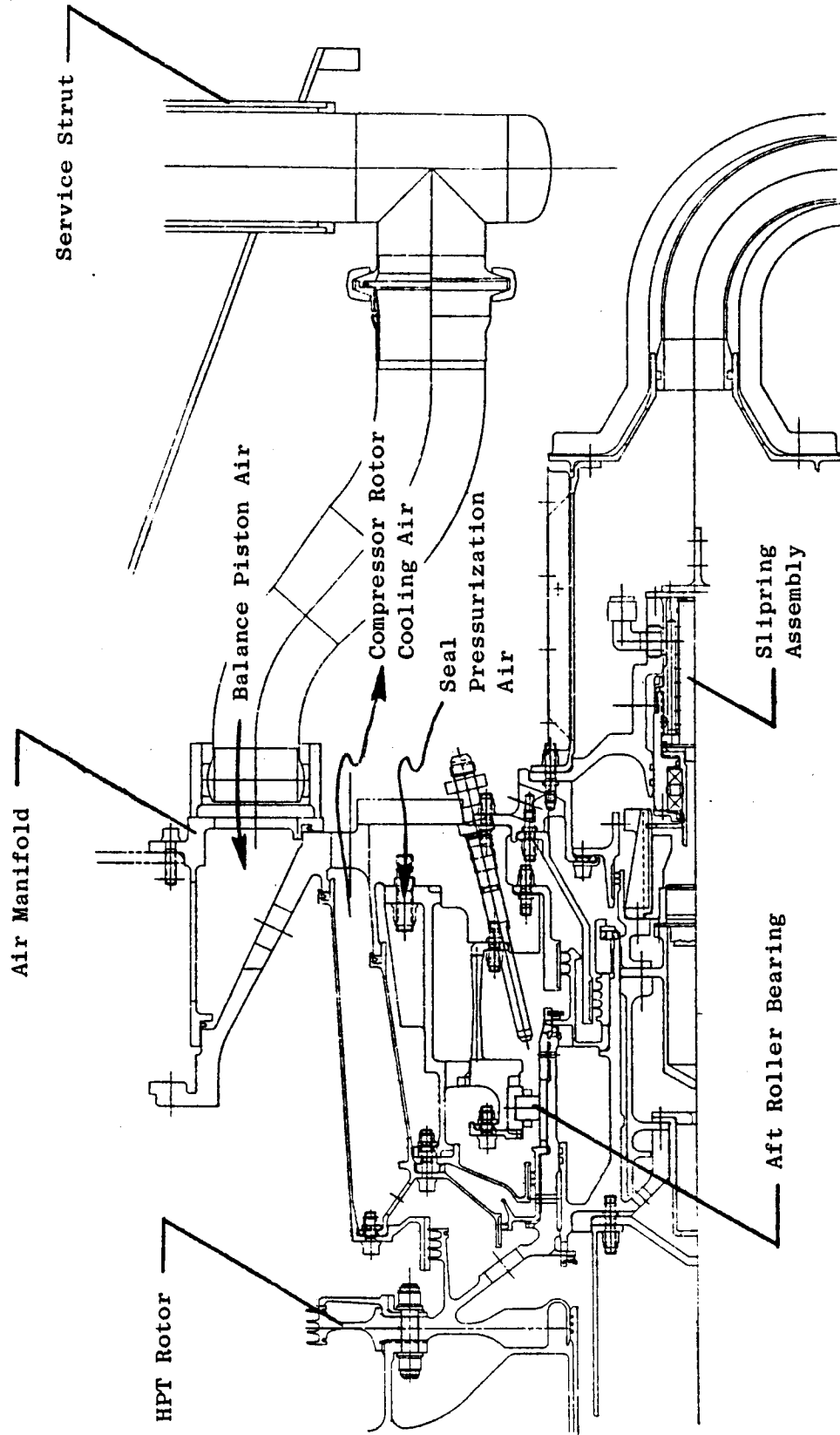


Figure 2.7-4. Core Engine Aft Sump.

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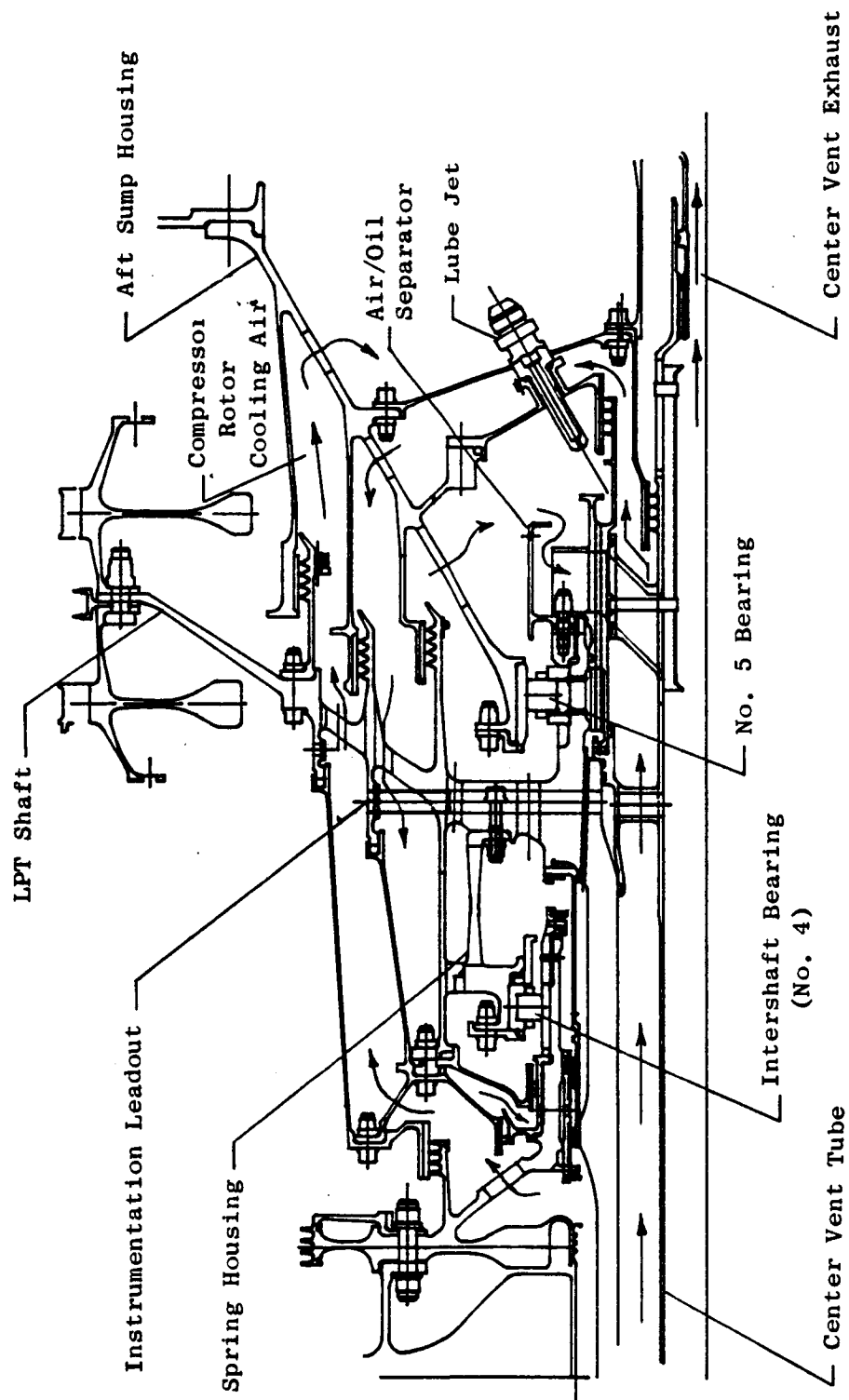


Figure 2.7-5. ICLS Aft Sump.

The lube system for the Core and ICLS engine is shown in Figures 2.7-6 and 2.7-7, respectively. The lube flows to the sumps of the Core engine have been revised from that previously reported and are given in Table 2.7-I along with the present status of the ICLS engine.

Table 2.7-I. Lube Supply Status of Core and ICLS Engine.

<u>Component</u>	<u>Core Lube Flow, gpm</u>	<u>ICLS Lube Flow, gpm</u>
Forward sump	4.0	6.2
Aft sump	2.0	2.6
AGB	2.9	2.9
Bypass oil	<u>7.9</u>	<u>5.1</u>
	16.8	16.8

The bypass oil will be directed to the pump inlet rather than to the lube tank as had previously been shown in the core lube system schematic.

The rotor thrust for the ICLS engine has also been updated and the thrust load on the HP and LP system bearings are shown in Figure 2.7-8.

As previously stated in the "Overall Objectives," this WBS will be included in WBS 2.7.1.2, and Lube System activity will be reported in this WBS in all future semiannual reports.

#### Work Planned

- Continue to coordinate lube system with other engine functions
- Continue to update secondary flow system and rotor thrust for both the Core and ICLS engine.

#### 2.7.2 Accessory Drive System

##### Technical Progress

Figures 2.7-9 and 2.7-10 show the cross section of the PTO and AGB, respectively. All hardware is now on order for the drive system and fabrication is proceeding.

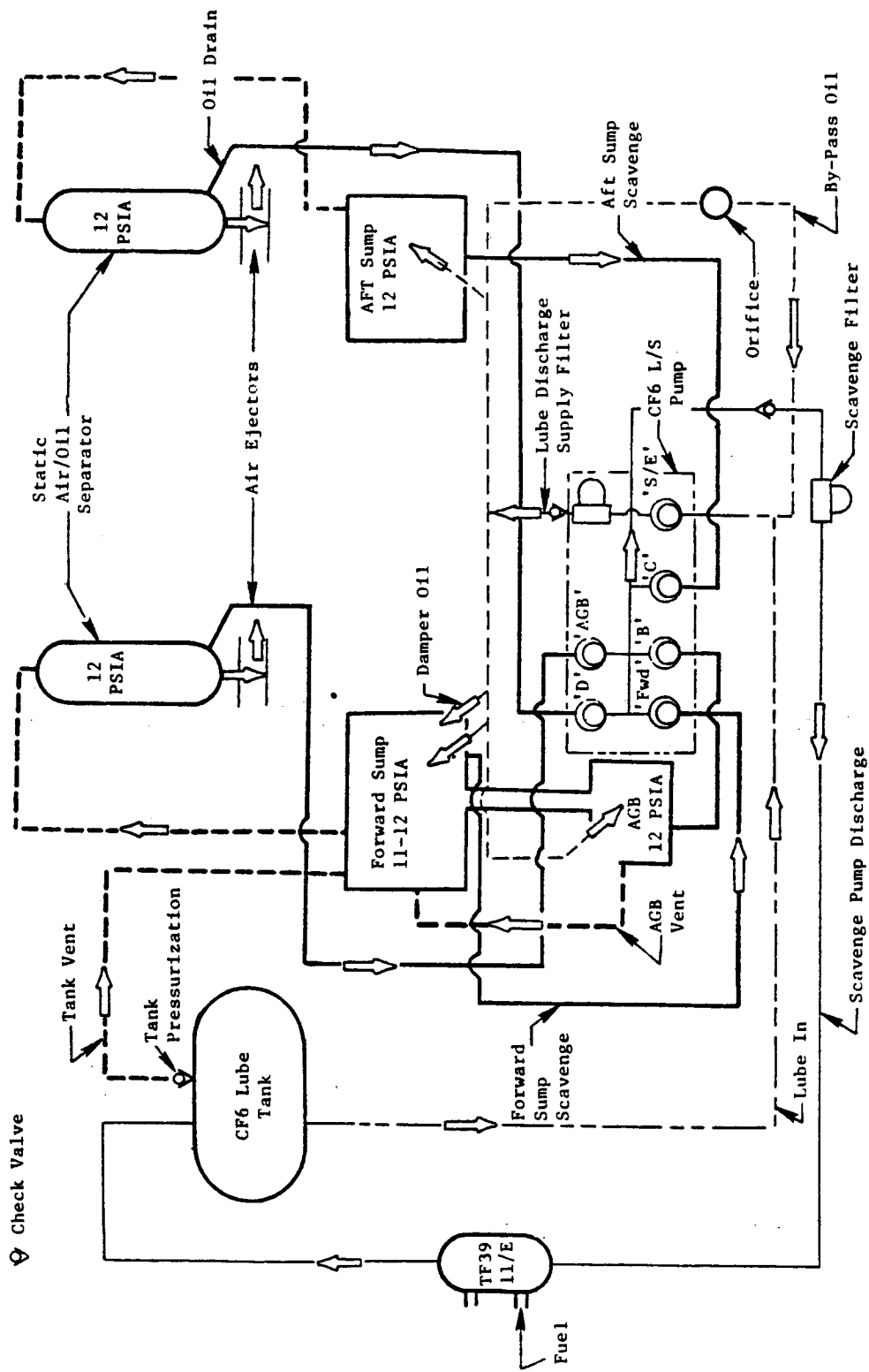


Figure 2.7-6. Core Engine Lube System Schematic.

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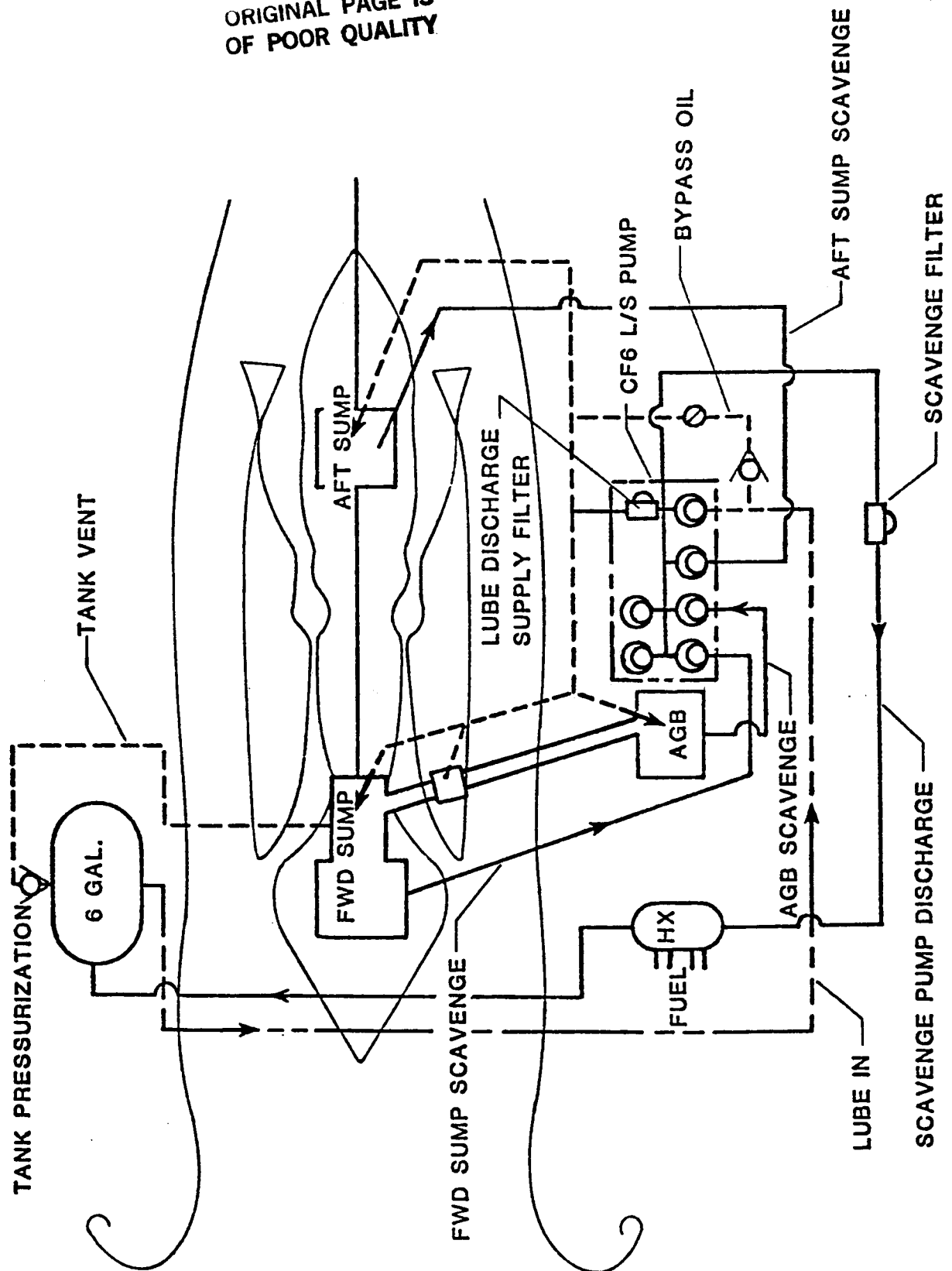
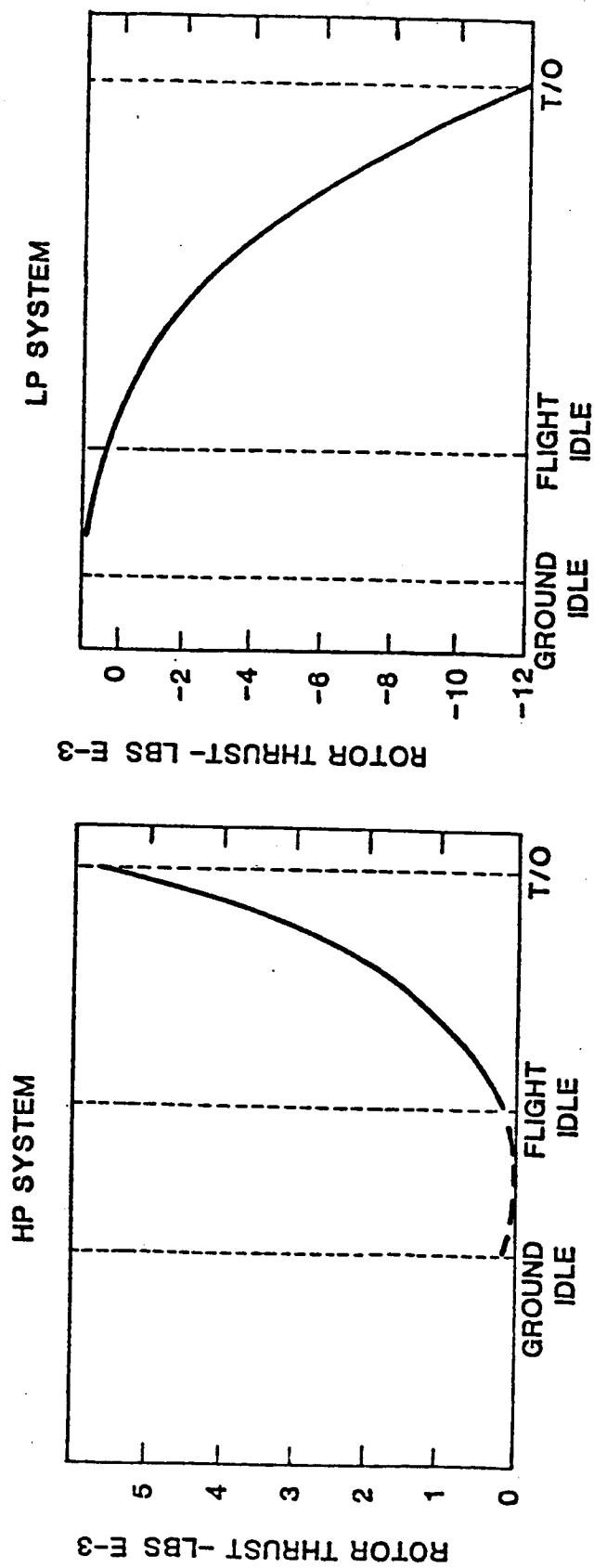


Figure 2.7-7. ICLS Engine Lube System Schematic.



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Figure 2.7-8. ICLS Engine Thrust Bearing Loads.

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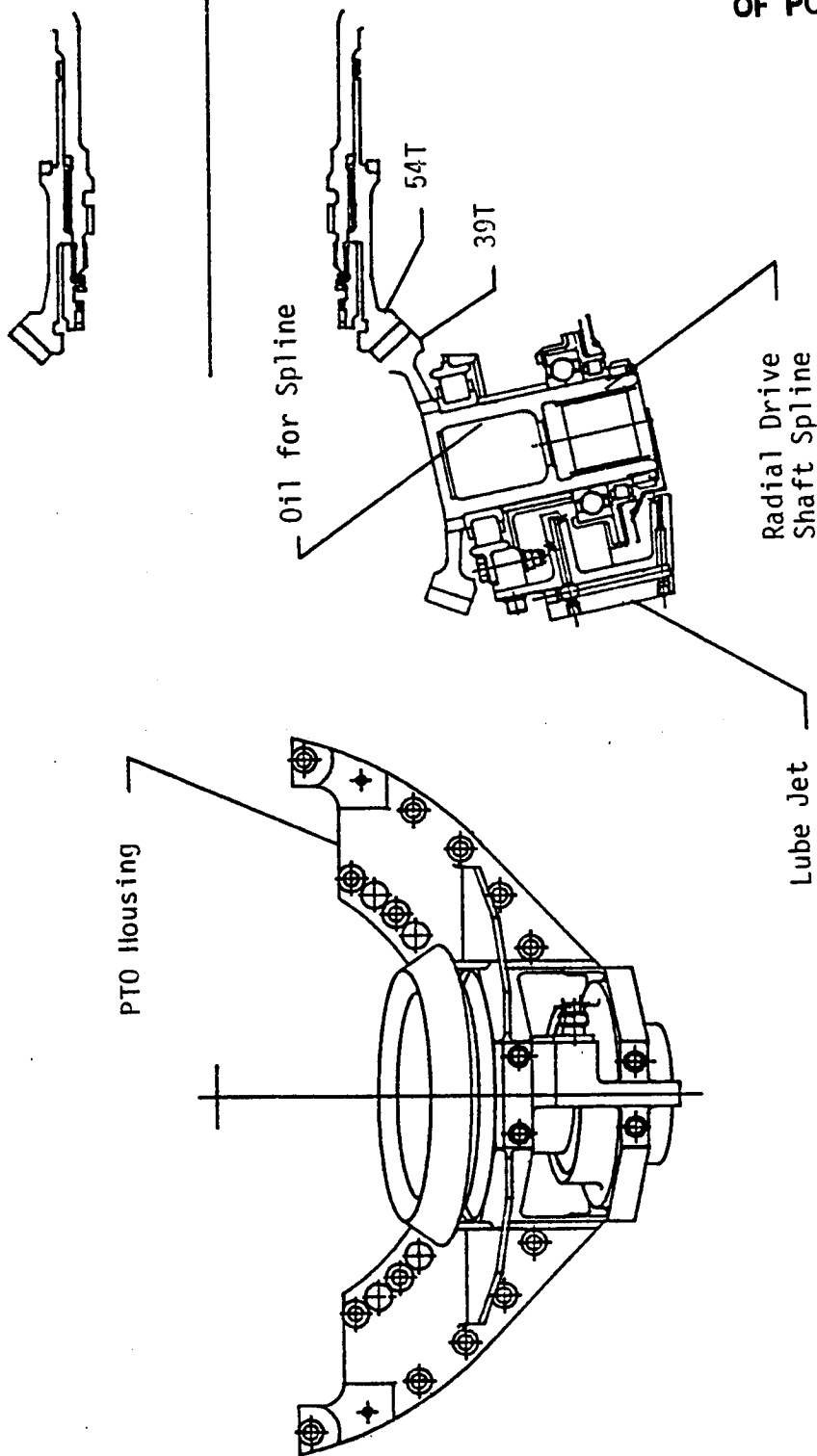


Figure 2.7-9. PTO Gearbox Assembly.

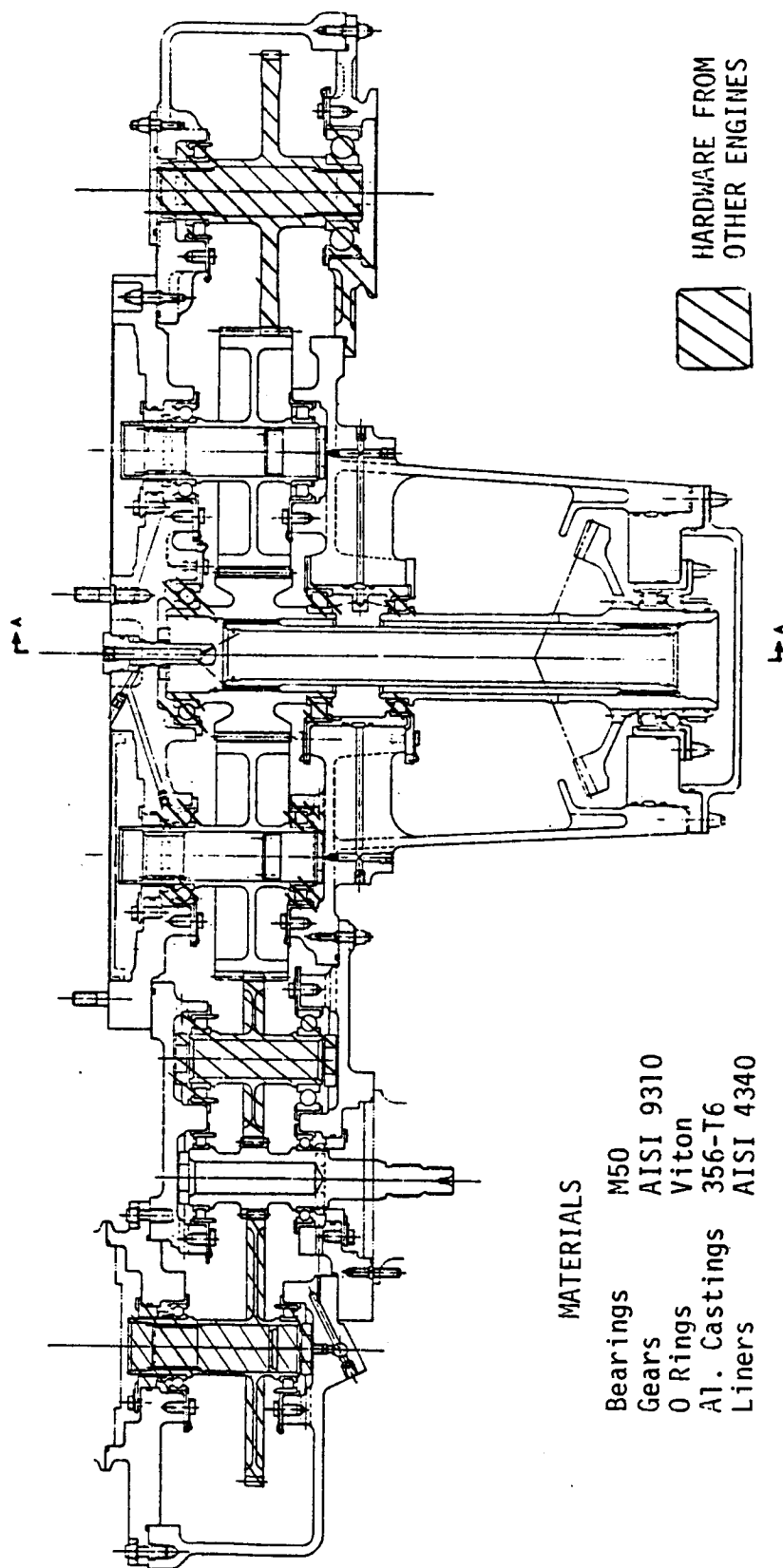


Figure 2.7-10. Core/ICLS Accessory Gearbox.

During the early part of this reporting period, a visit to the casting vendor of the main housing casting for the AGB revealed two small errors in the first casting that were corrected by welding. Casting has been shipped to the machining source.

Photographs have been taken of the final gear patterns of the PTO gearbox at the gear vendor. These photographs will be used as guides during the gearbox assembly.

#### Work Planned

- Continue procurement of all hardware.

### 2.7.3 Configuration Design

#### Technical Progress

All detail drawings for the configuration hardware required for the Core engine have been issued and hardware is in the process of manufacture.

Detail drawings for the ICLS engine configuration requirements are in process and the last drawings should be issued during the next reporting period.

The detail drawing for the pressure bulkhead required for the ICLS engine has been issued. We are presently working with vendors to reduce cost.

Analysis work is in process for the Core area junction box. Detail drawing is also in process.

#### Work Planned

- Complete drawings for the ICLS engine configuration
- Continue to procure hardware.

### 2.7.4.3 Intershaft Bearing Test

#### Technical Progress

This program has been cancelled in the June 1981 replanning effort. The bearing proposed for this test, although close in size to the E<sup>3</sup> intershaft

bearing, is not the exact configuration. This, along with the inability to run Core engine conditions (stationary outer race), influenced the decision to cancel further effort on the program. Bearing internal clearance will be established analytically.

#### 2.7.4.4 Bearing Underrace Cooling Test

##### Technical Progress

Figure 2.7-11 shows a cross section of the test rig with the test bearing in place.

All rig hardware is available and buildup has been started. Two test bearings have been delivered from the bearing vendor and have been prepared for assembly.

A "Test Project Sheet" has been written which outlines the test desired. Bearing temperature characteristics and heat rejection will be determined during this test.

##### Work Planned

- Complete testing.

#### 2.7.5 Bearing, Systems, Drives, and Configuration Fabrication

##### Technical Progress

All hardware that is needed in the second build of the 1-10 compressor rig is available and is in various stages of assembly.

Hardware required for the Core engine sumps and drive system is on order and fabrication is proceeding. Normal manufacturing problems which are encountered occasionally have not been major and have been resolved to date.

##### Worked Planned

- Continued procurement of Core engine hardware.

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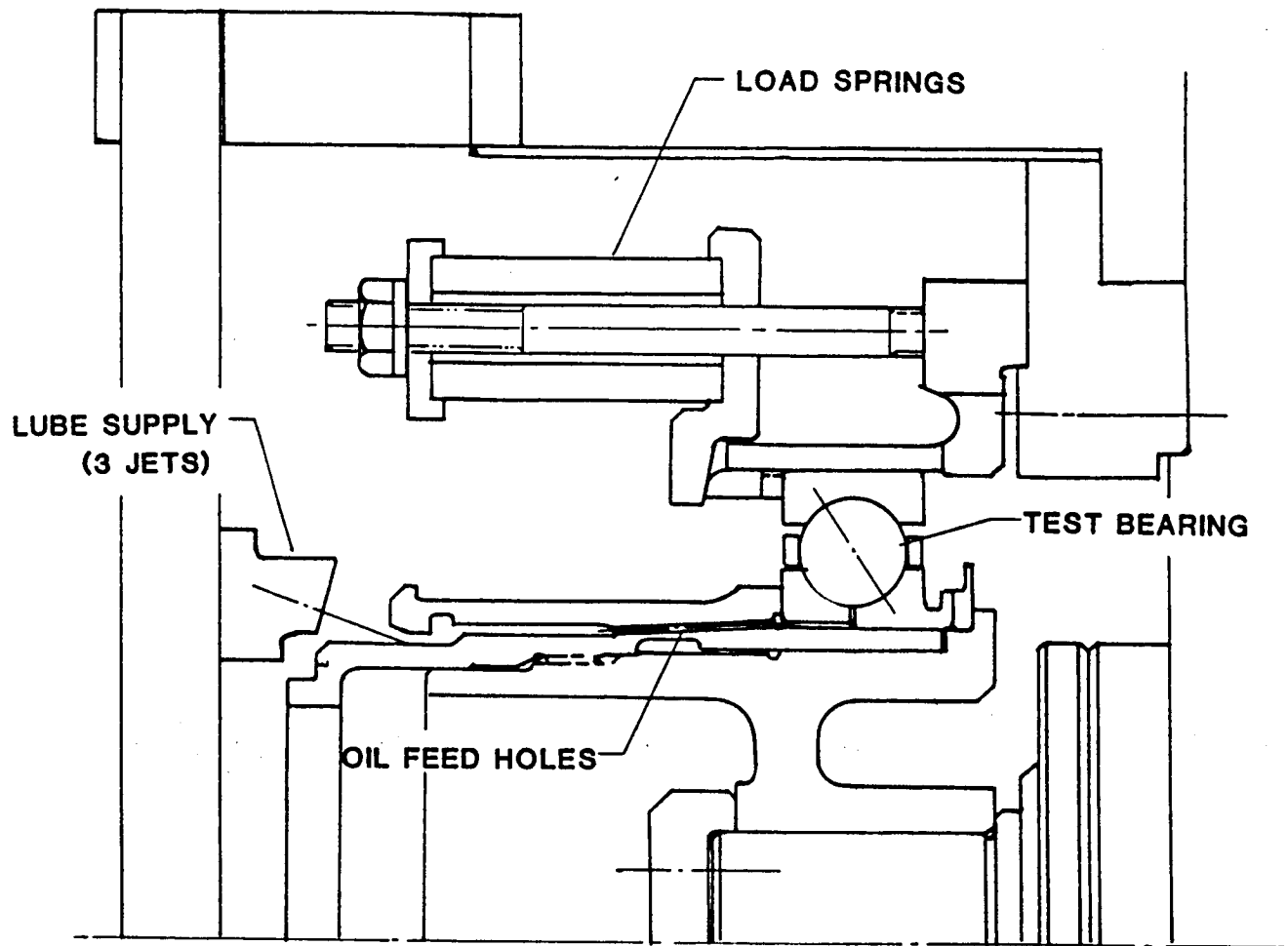


Figure 2.7-11. Under Race Cooling Test Rig.

## 2.8 CONTROL AND FUEL SYSTEM

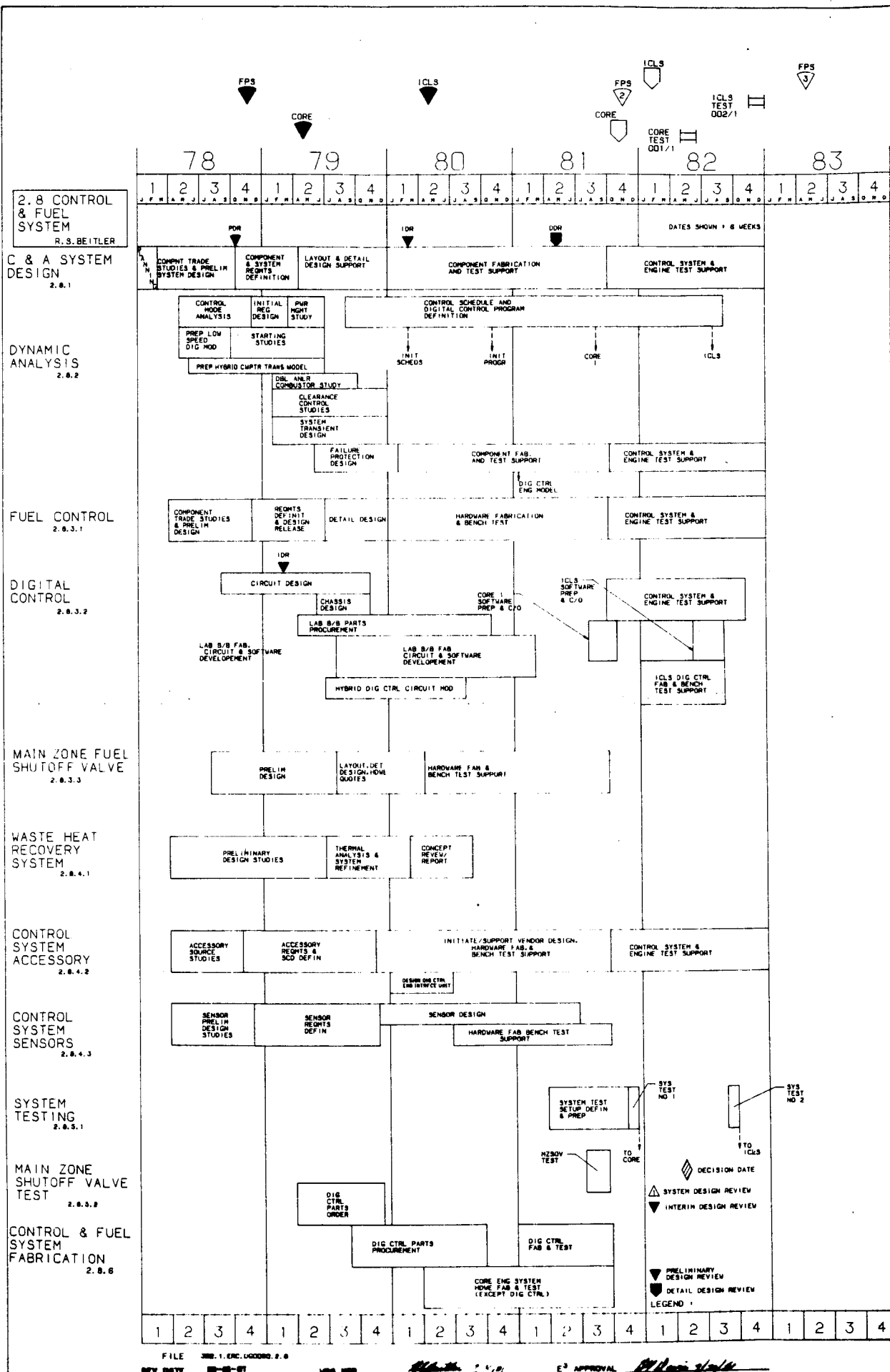
### Overall Objectives

The primary objective of the control and fuel system program is to define a system for E<sup>3</sup> which thoroughly exploits the engine's fuel conservation features that provides operational capability and reliability which is equal to or better than that provided by current transport engine control and fuel systems, and which employs digital electronic computation suitable for interfacing with an aircraft flight control computer. An additional objective is to demonstrate the system functionally on the core and ICLS engines.

The proposed control and fuel system for the E<sup>3</sup> is based on many of the proven concepts and component designs used on the CF6 engine family. The major difference is in the addition of full-authority digital electronic computation, which provides significant improvements in control flexibility, accuracy, and aircraft/engine integration capability.

The digital control is expected to contribute to the low fuel consumption of the E<sup>3</sup> by providing automatic power management and optimum control of variable geometry on the engine over the full range of operating conditions which will be encountered. The control will also help reduce deterioration in engine efficiency by automatically preventing engine overspeed, overpressure, or overtemperature.

The E<sup>3</sup> fuel system employs fuel handling concepts that are basically similar to the CF6. In the flight design, an engine-driven, positive-displacement gear pump with an integral centrifugal boost element is used for pumping. A pump-mounted heat exchanger, downstream of the gear pump element but upstream of the system filter and fuel metering section, provides the dual functions of cooling the engine lube oil and heating the fuel to prevent filter icing. Fuel metering is accomplished by a fuel metering valve/bypass valve combination that sets engine fuel flow and returns excess fuel to the inlet of the gear pump element. Downstream from the metering valve, excess heat from the air being bled from the compressor for use in the aircraft environmental control system (ECS) is transferred into the fuel, thereby improving engine system efficiency by returning waste heat to



the engine cycle and reducing the ECS air cooling requirements. After passing through this heat exchanger, the metered fuel is divided as necessary to accommodate the double-annular combustor.

The system also controls several variable geometry elements on the engine including the variable stator vanes and starting bleed valves on the compressor, and the air valves for controlling clearance in the compressor, HP turbine, and LP turbine.

Engine starting will be accomplished using a gearbox-mounted, air-turbine starter similar to that used on the CF6. Scheduling of fuel flow during the starting sequence will be done by the digital control, which will also provide ignition sequencing logic by energizing the ignition as a function of a starting command input and de-energizing it when the engine has accelerated beyond the point where ignition is needed. The ignition will also be automatically energized if the digital control detects deceleration conditions that indicate a burner blowout has occurred.

#### Development Approach (Reference WBS Spread/Schedule Sheet)

The control and fuel system design and development effort began with a preliminary design phase in which various system and component design options were defined and evaluated. Particular emphasis was placed on the method of incorporating advanced technology features such as the full authority digital control, air/fuel heat exchange for waste heat recovery, active clearance control, and fuel flow division for the double-annular combustor. The initial study work resulted in the definition of a preliminary control system design in late 1978. A preliminary design review of this system was held at NASA-Lewis in October 1978 and the design was further reviewed as part of an overall engine preliminary design review in November 1978.

With the basic system design concepts established, the next task was to define detailed system and component requirements for the demonstrator engine program and proceed with detailed component design. This task, which was essentially completed in 1979, involved several different types of activity. In the system design area, the basic system and component

requirements were established and documented. Concurrently, a number of supporting analytical activities were carried out under the Dynamic Analysis subprogram using computer simulations to investigate engine and control characteristics and to define requirements, particularly those related to control stability and response. Meanwhile, component design and development activity was proceeding as described below.

Fuel control design and development is being done under WBS 2.8.3.1. For the core and ICLS, a modified F101 fuel control will be used. Detailed requirements for the control have been defined and transmitted to the control vendor. Control modifications were defined in detail, the modifications reviewed with NASA in March 1980, and implementation of the modifications is underway for the core engine under WBS 2.8.6; and for the ICLS under WBS 4.2.4.

Design of the digital control is being carried out under WBS 2.8.3.2. The basic control design process includes initial circuit design, experimental circuit refinement using a laboratory breadboard control, and chassis design. Because construction of the laboratory breadboard requires procurement of electrical parts prior to the control system detailed design review (DDR) scheduled for early 1981, an interim design review (IDR) of the digital control was conducted in March 1979.

Construction of the breadboard was completed in March 1981 and it is being used to check out and refine control circuits and to check out control software.

The digital control resulting from the above design effort will be an off-engine unit suitable for both the core and ICLS engines. It will be built and tested under WBS 2.8.6. This control will definitely be used on the core engine but it is planned that an on-engine unit, constructed under a separate program, will be used for the ICLS engine. The on-engine unit will incorporate an advanced hybrid electronic packaging concept.

The main zone fuel shutoff valve covered by WBS 2.8.3.3 is a new valve designed to assist in the fuel flow division required by the double-annular

combustor. Detailed design of this valve was completed and reviewed with NASA in early 1980. Fabrication and test of the valve for the core engine is proceeding under WBS 2.8.6 and 2.8.5.2, respectively.

The air/fuel heat exchanger work under WBS 2.8.4.1 began with thermal model studies to examine, in detail, the potential fuel savings available by transferring heat from the compressor bleed air to the engine fuel. Early in the second quarter of 1980, the results of these studies were assessed by NASA and General Electric and a decision was made to delete the hardware demonstration originally planned for the waste heat recovery concept. This was done primarily because the concept, although unique in function, is implemented with standard components that do not represent new technology.

Design of control system accessories and sensors is being carried out under WBS 2.8.4.2 and 2.8.4.3. These components do not represent advanced technology and consequently, for economic reasons, will be modifications of existing designs. Detailed component requirements were established in 1979 and transmitted to the appropriate design organizations (mostly outside vendors) to serve as a basis for detailed definition of component modifications. The designs were reviewed in a March 1980 IDR and released for procurement.

The system and component designs resulting from all of the effort described above were reviewed and approved in a Detailed Design Review at NASA-Lewis in April 1981 and the designs are being implemented in hardware. A full set of control system components will be available soon and will be assembled into a complete system for bench testing late this year. Subsequently, the components will be installed for operation of the core engine.

Control system hardware from the core engine will be used on the ICLS except that an on-engine digital control will be used, as noted previously, and a fan speed sensor and LP turbine clearance control subsystem will be added. The ICLS control system components will also be bench tested as a complete system prior to operation on the engine. Additional control system hardware will be procured to provide a limited, yet adequate, supply of spare parts.

## 2.8.1 Control System Design and Analysis

### Technical Progress

No significant control system design changes were made during this reporting period. A Detailed Design Review of the system was held at NASA-Lewis in April and there were no findings that necessitated design change.

In conjunction with the DDR, a system failure analysis was made. It was focused on the core and ICLS designs. No failures with clearly destructive effects on the engine were found. The analysis verified that the systems' fail-safe features, such as the deliberate drift of electrohydraulically controlled variables in a safe direction in the event of electrical power or electrical interconnection failures, have been designed properly. The analysis also verified that the incorporation of a hydromechanical back-up fuel and stator control is justified.

The failure analysis did show that failures of some control input sensors or sensor-to-control connections can have undesirable effects. Such problems, however, can be virtually eliminated by incorporating sensor failure protections strategy in the digital control such as the Failure Indication and Corrective Action (FICA) proposed for the ICLS. This FICA strategy assesses sensor outputs relative to a simplified engine model in the digital control memory and substitutes model values for faulty sensor outputs. The core engine control strategy is being prepared without this type of FICA because the reduced scope of the core control (that is, no LP rotor functions, test facility control of compressors stators) makes it less necessary and programming cost savings will result. .

Another task completed during this reporting period was the detailed design of electrical cables. Layout drawings were made to define optimum cable routing, cable lengths, and connector orientations. Detailed drawings of individual cables were then prepared. Generally AWG20, stranded, nickel-plated copper wire is being used. Functionally associated wires are run as metal shielded, twisted pairs and triplets within cables consisting of a glass fiber braid covered by an outer metallic (nickel) braid. Connectors

are of stainless steel and are mechanically attached to the outer metallic braid to carry handling loads and provide shielding grounds. A typical cable is shown in Figure 2.8-1.

#### Work Planned

- Support core engine digital control programming and bench test
- Support core engine control system test
- Prepare core engine control system test report
- Support core engine assembly and test preparation.

#### 2.8.2 Dynamic Analysis

##### Technical Progress

During this reporting period, the subidle engine model, which was prepared earlier in conjunction with engine starting analysis, was utilized in a unique manner to analyze data during the full-scale compressor test. The model was used in conjunction with the test facility data system and was modified to accept actual test data as inputs to the compressor simulation. After each data point, the model was used to calculate matching engine characteristics such as fuel flow, turbine temperatures, and available margin for acceleration. This procedure proved to be quite successful and provided much more rapid assessment of subidle compressor characteristics as they relate to the complete engine than had previously been possible.

After completion of the compressor test, the data which was gathered as noted above was used to refine the compressor simulation in the subidle model. Similar refinement was done in the turbine simulation based on data from air testing of the HP turbine. The refined subidle model will be used to re-examine engine starting characteristics.

Another task recently completed in the Dynamic Analysis area was the definition of three schedules for the hydromechanical backup control as outlined below.



### Power Lever Schedule

This schedule establishes the core rpm versus power lever angle relationship set by the backup control. In defining it, a schedule was first defined for the digital control and then the backup control was set slightly lower. This was done because it was deemed preferable for the engine to decelerate a small amount in the event of a digital control malfunction causing switch-over to the backup control. The primary design criterion for the schedule was that its slope be set low for ease of test point setting in the 93% to 100.5% speed range in which much of the core engine testing will be done.

### Acceleration Fuel Schedule

Data from the subidle engine model and the engine cycle deck in combination served as the basis for this schedule which establishes the maximum allowable fuel flow as a function of compressor rpm, inlet temperature, and discharge static pressure. The basic schedule was set midway between the fuel flow required for steady-state operation and the flow that will stall the compressor. It was modified downward in the low speed and high speed region to prevent turbine overtemperature, and a high speed cutback was included to provide redundant overspeed protection (separate speed sensing elements for fuel scheduling and speed governing).

### Compressor Stator Schedule

This schedule defines the required stator angle characteristic as a function of compressor rpm and inlet temperature. Because control procurement considerations required that the schedule be defined before completion of all compressor exploratory testing (second full-scale component test and core engine test yet to be run), the schedule was set 5° in the closed or safe direction from the schedule currently considered most likely by compressor aerodynamic designers.

Each of the above schedules was translated into the form required by the computer-controlled machines that will be used for schedule cam manufacture. The schedules were delivered on tapes suitable for direct application on the machines.

#### Work Planned

- Additional engine starting analysis using the refined subidle engine model
- Support digital control software checkout and core engine system testing.

#### 2.8.3.1 Fuel Control

#### Technical Progress

The modified F101 fuel controls to be used on the E<sup>3</sup> demonstrator engines were in preparation at Woodward Governor Company during this period. Schedule cam data was recently supplied as noted in the previous section, and the two controls will be completed, bench tested, and shipped to GE for system testing in November 1981.

During this reporting period, a problem was discovered with the new relief valve springs designed to raise the maximum pressure capability of the two F101 fuel pumps to be used in the E<sup>3</sup> program. The springs were found to have marginal travel before reaching their solid height. The spring was redesigned and is being procured.

Progress was made in the acquisition of other hardware elements associated with the fuel control. Parts for the custom-designed E<sup>3</sup> fuel transfer valves and stator transfer valves were received, the valves were assembled, and they will soon be bench tested and delivered for system testing in November. Figure 2.8-2 is a photograph of the stator transfer valve. The electrohydraulic fuel and stator control servovalves were received from vendors as were the refurbished hydromechanical F101 core inlet temperature sensors which will be used with the backup control.

#### Work Planned

- Complete bench test of fuel system hardware and deliver for system test
- Support system test
- Design the mechanical compressor stator feedback for the hydro-mechanical backup control.

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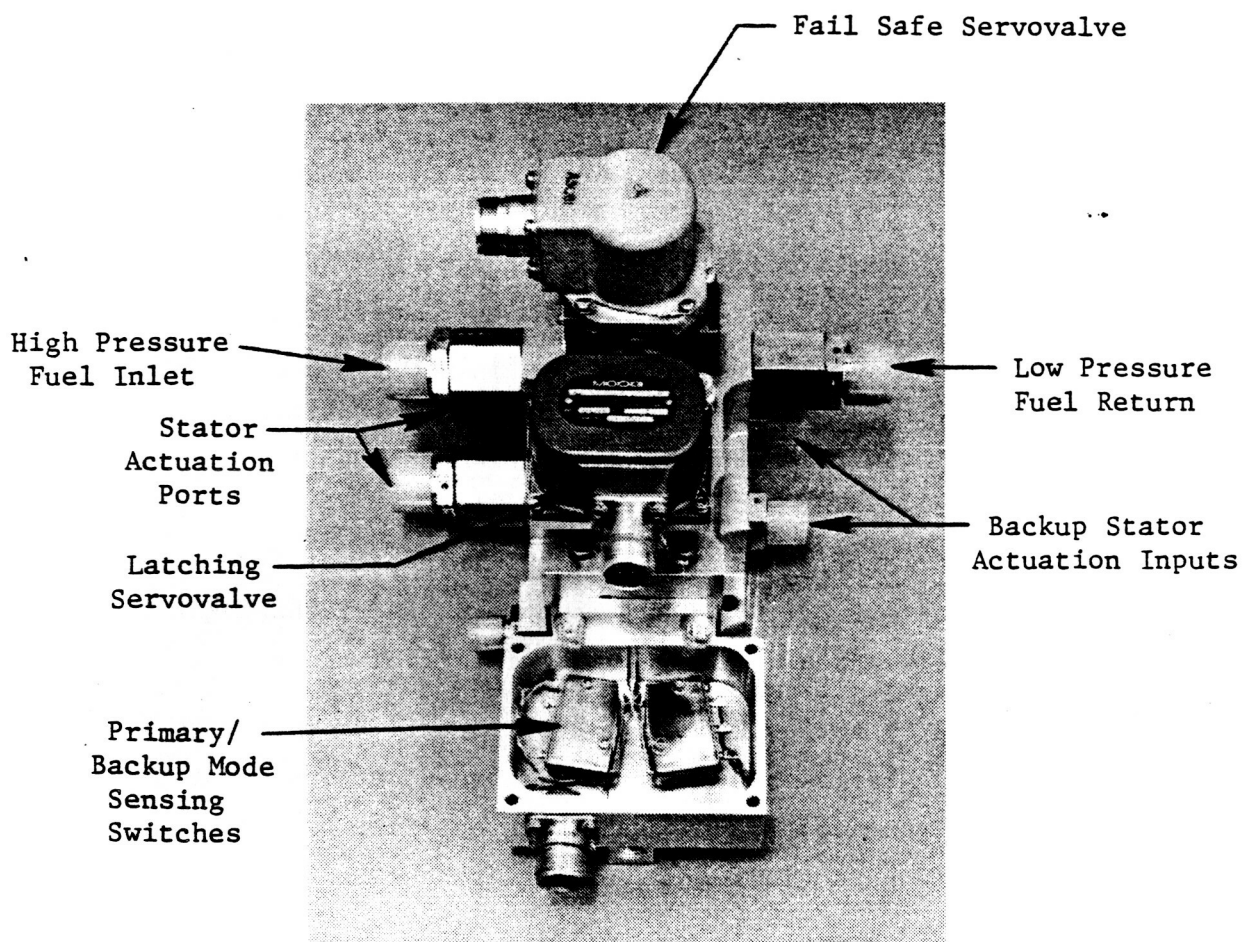


Figure 2.8-2. Stator Transfer Valve.

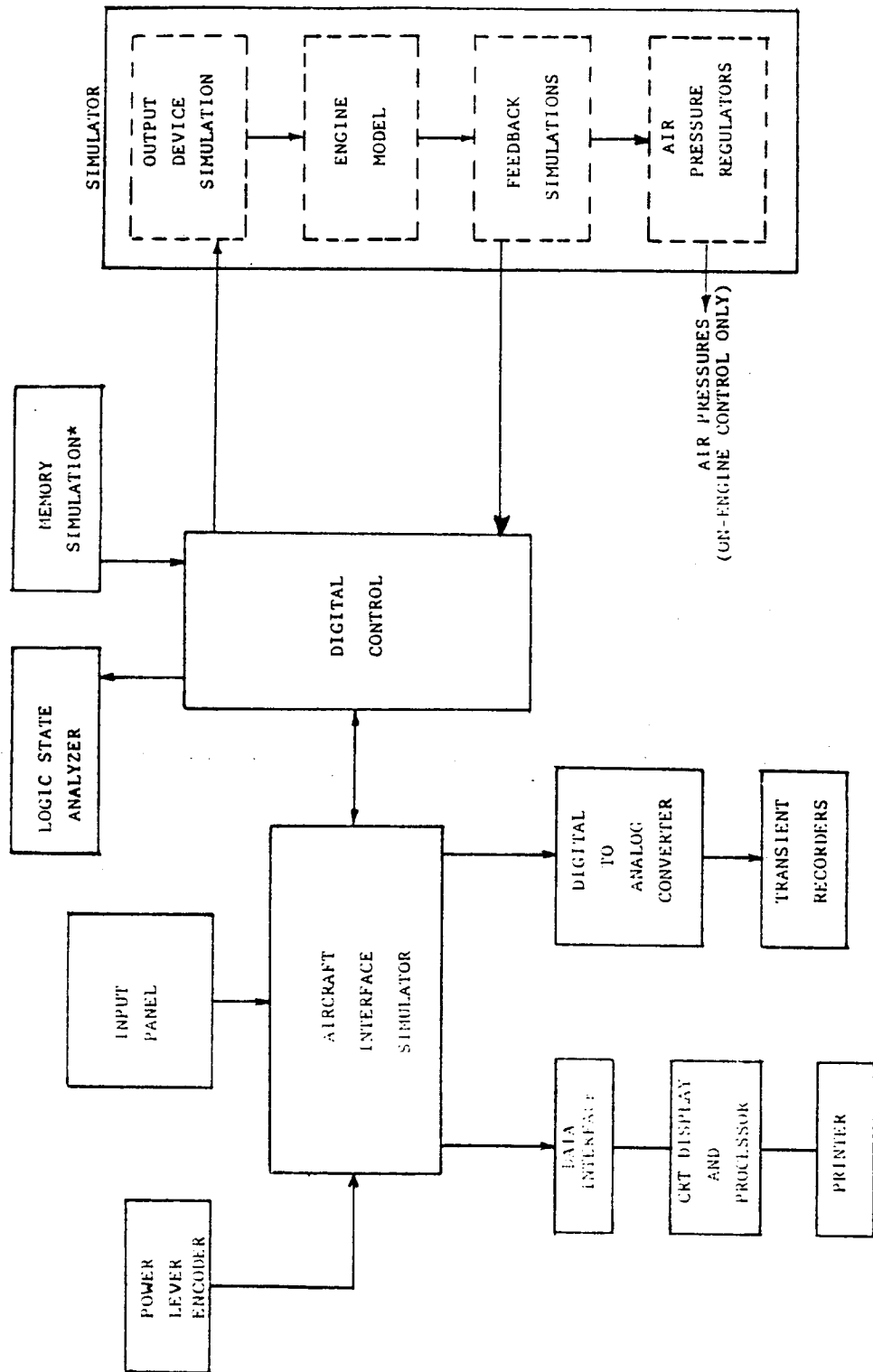
### 2.8.3.2 Digital Control

#### Technical Progress

Checkout of the initial digital control software was completed during this reporting period. This software was a preliminary version of the ICLS software except that it did not include FICA sensor failure protection strategy. It was made up of 5225 words of program memory and utilized 355 of the 512 available read-write memory locations in the control.

The test setup used for checkout of the software is shown in Figure 2.8-3. The E<sup>3</sup> digital control breadboard and breadboards of the input panel and aircraft interface simulator were used. A bench power supply was used because the E<sup>3</sup> power supply noise problems discussed below were not yet solved. The software program was stored in the reprogrammable memory simulator and the entire setup was run with the control loops closed through the simulator. Discrepancies in the software were methodically identified and corrected over a relatively short period of time and, once all corrections were made, the system ran satisfactorily. Figure 2.8-4 is a data trace, showing a typical acceleration and deceleration during the latter part of the checkout.

The E<sup>3</sup> power supply noise problem discovered earlier persisted through much of this reporting period. A power supply breadboard separate from the basic digital control breadboard was used to investigate the problem and potential solutions. One obvious problem was that the 28 volt d.c. section of the power supply was not compatible with the 5 volt fine regulator that it shared with the alternator supplied section. This switching regulator was designed for the input characteristics provided by the alternator and it drew excessive current from the 28 volt d.c. supply during part of the switching cycle. To remedy this, a separate 5 volt regulator circuit employing a d.c.-to-d.c. converter with variable pulse width regulation was incorporated in the 28 volt d.c. section and connected through diodes to the output rather than the input of the alternator supplied switching regulator. This solved the high current draw part of the problem. A block diagram of this configuration is shown on Figure 2.8-5.



\*NEEDED WITH BREADBOARD CONTROL ONLY

Figure 2.8-3. Digital Control Test Setup.

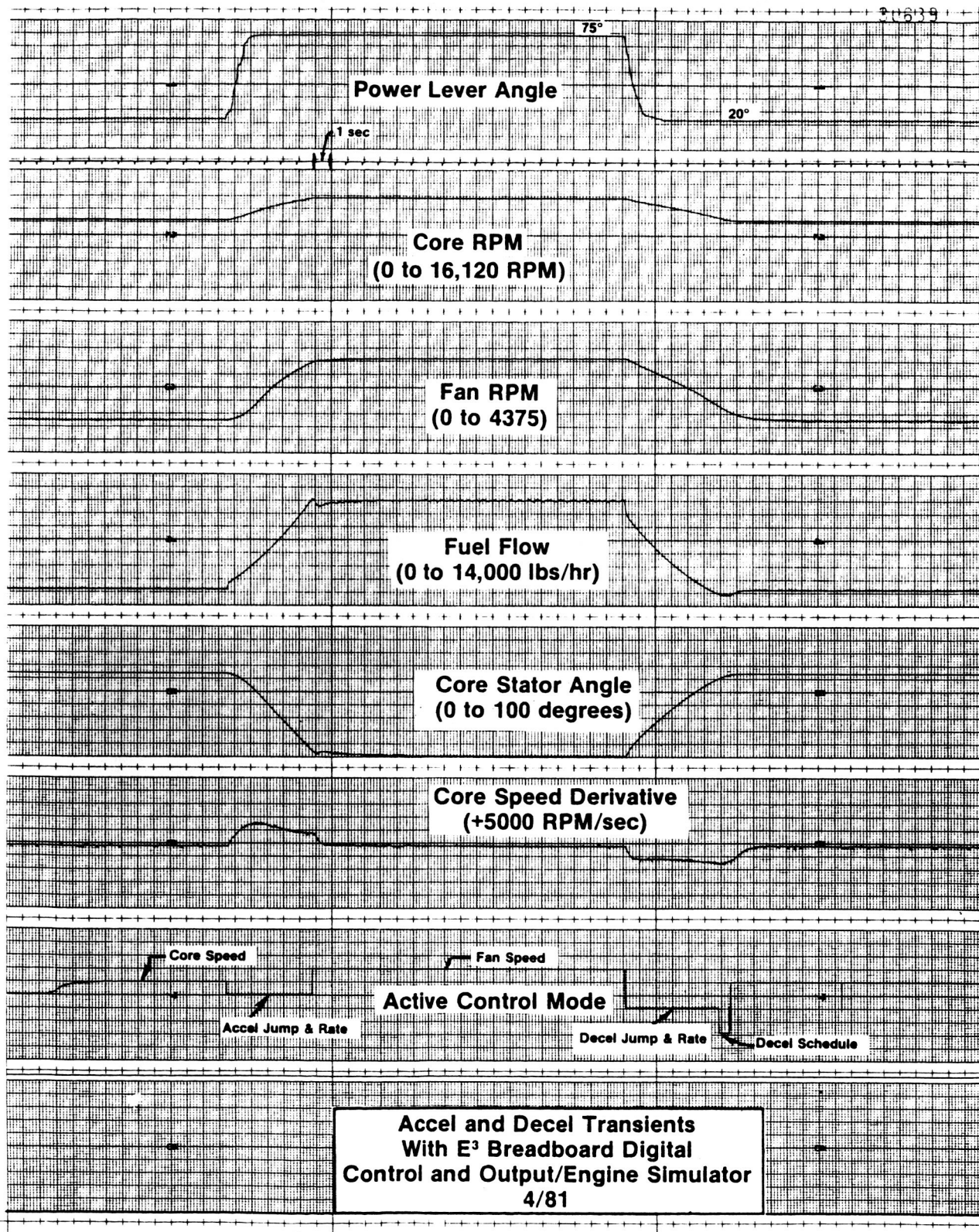


Figure 2.8-4. Digital Control Checkout Transients.

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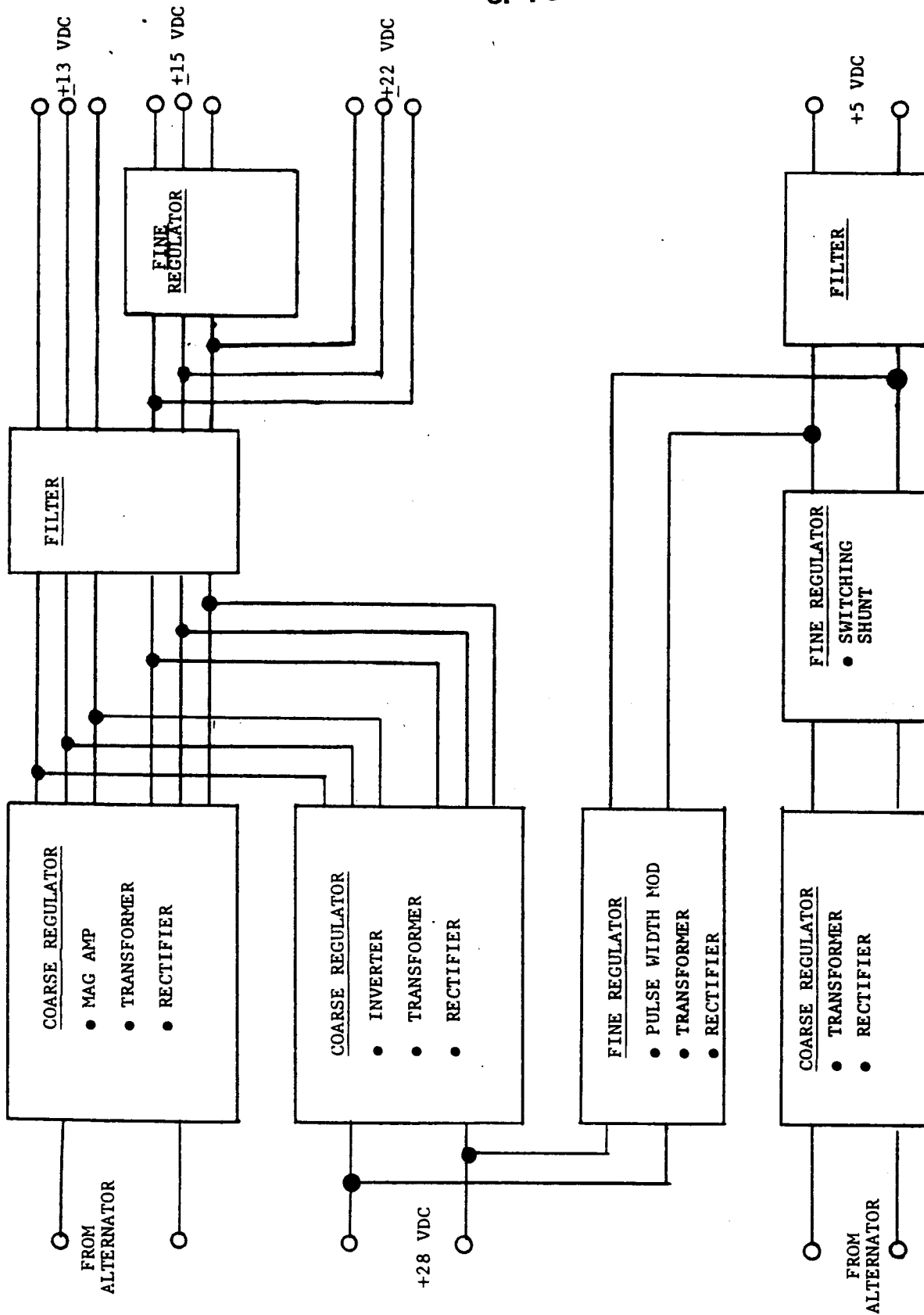


Figure 2.8-5. Digital Control Power Supply.

The redesigned power supply was incorporated in the control breadboard and the software was run as it had been previously with the bench power supply. This running showed that the noise generated by the 5-volt switching regulators in the power supply showed up in the analog section of the control resulting in unsatisfactory stator positioning due to noise in the temperature input to the schedule. Modifying the physical arrangement of the control to get further separation between the power supply and the analog section did not eliminate the problem. The breadboard control has now been further modified so that the power supply is metallically shielded from all other parts of the control and from all signal inputs. Testing of this arrangement was about to begin as this reporting period ended, and it is expected to be successful.

Construction of the digital control hardware to be used on the core engine has been proceeding. All of the key peripheral units have been completed and checked out. Included in this category are the aircraft interface unit, the operator panel, the data interface unit, the data microprocessor and display units, and the printer. Completion of the Control Room Unit (CRU) which houses the major digital control elements has been held up until the power supply problem is resolved. All of the CRU circuit boards except those associated with the power supply have been completed and checked out. Once the power supply problem solution is verified, the resulting design will be incorporated in the CRU and the unit will be completed and checked out.

Preparation of the software for the core engine is also proceeding. The initial software which was discussed above is being modified to remove all LP system related functions and compressor stator control functions. The core software will be checked out using the test setup shown in Figure 2.8-3 and then it will be put into the core engine CRU memory for bench test and system test before the end of this year.

#### Work Planned

- Verify that the metallic shielding of the power supply eliminates the control noise problem
- Complete the check out core engine control software
- Support digital control bench test and system test.

### 2.8.3.3 Main Zone Shutoff Valve

#### Technical Progress

All of the component parts for the main zone shutoff valves and pilot zone reset valve have been received and the valves are being constructed. A photograph of the pilot zone reset valve is shown on Figure 2.8-6. The valves will be bench tested individually and will be available for system test in November.

#### Work Planned

- Support bench test of main zone shutoff and pilot zone reset valves.

### 2.8.4.2 Accessory Design

#### Technical Progress

Virtually all of the activity here has been associated with vendor fabrication and delivery of hardware. Manufacture of the only custom-designed E<sup>3</sup> accessory, the compressor clearance control valve, is complete and the two units ordered have been received. A photograph of one of these units is shown in Figure 2.8-7. The other accessories are either existing components or modifications of existing components, and most have been received. The only ones not received are the butterfly valves to be used for starting bleed and turbine clearance air control and some of the pneumatic check valves. These are all expected by early October.

#### Work Planned

- Support system testing.

### 2.8.4.3 Sensor Design

#### Technical Progress

Design of the T3 thermocouple probe has been completed. Figure 2.8-8 is a schematic cross section showing this probe and its installation. The probe

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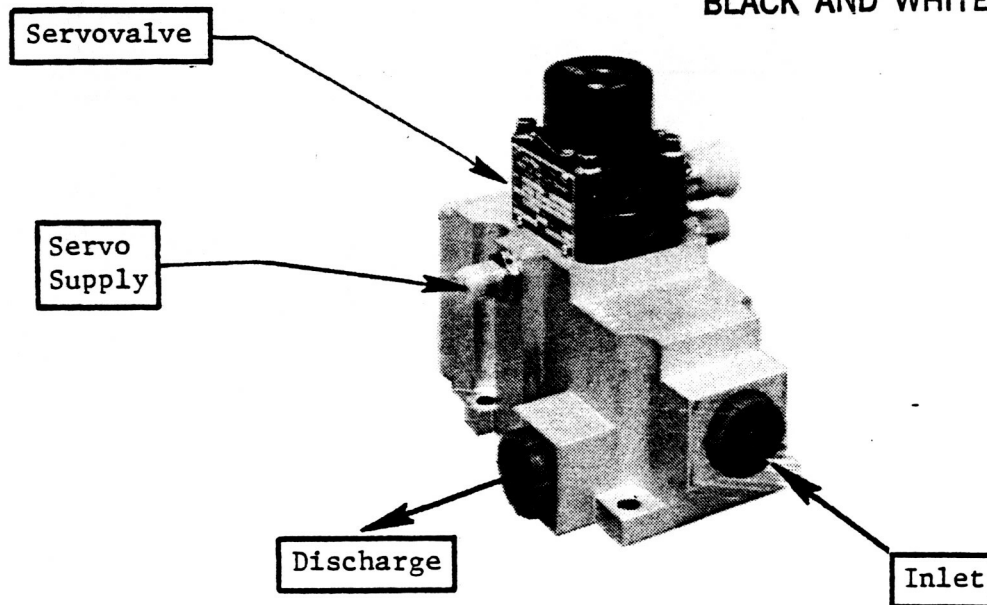


Figure 2.8-6. Pilot Reset Valve.

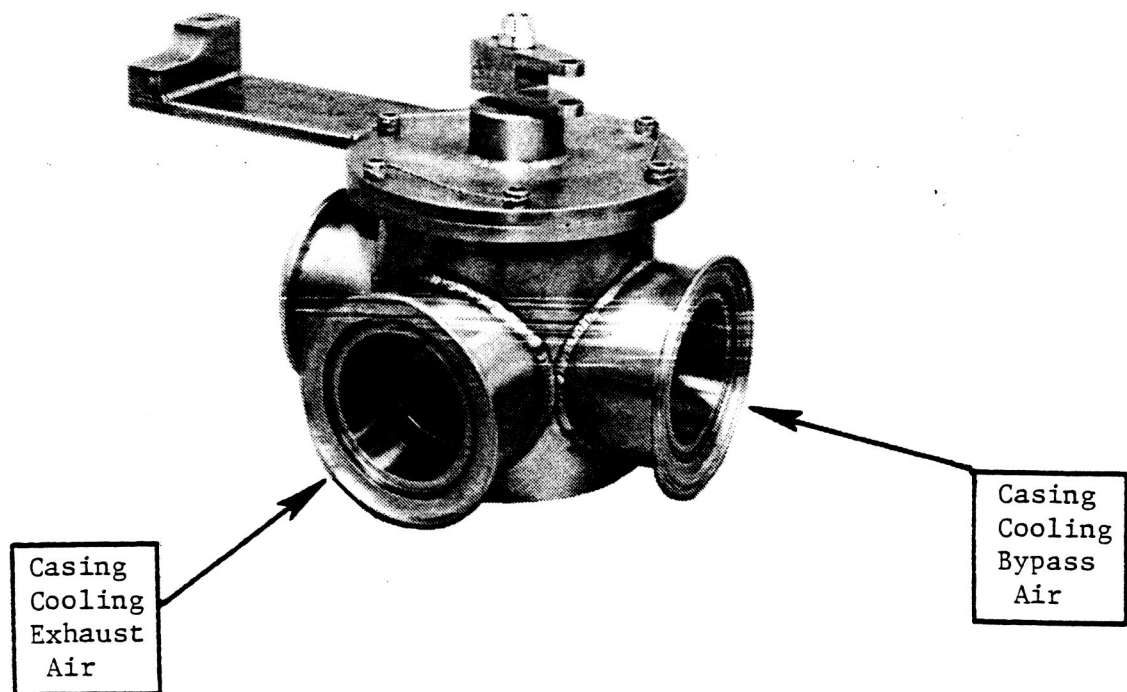


Figure 2.8-7. Compressor Clearance Control Valve.

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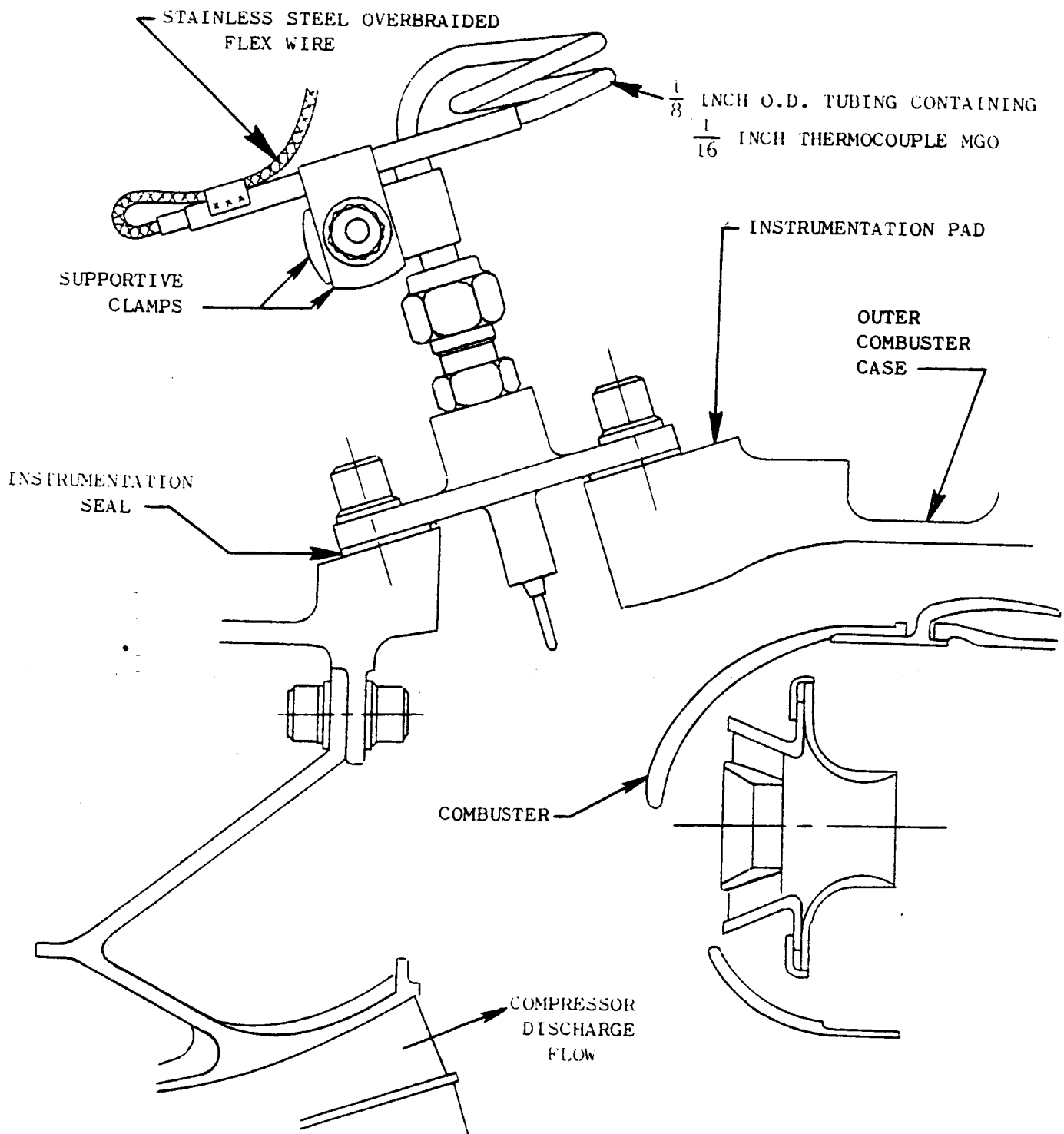


Figure 2.8-8. Compressor Discharge Temperature (T3) Sensor.

contains a chromel-alumel thermocouple junction which provides a signal to the digital control for use in calculating turbine inlet temperature and in the FICA sensor failure protection strategy.

Some design coordination has been necessary relative to the compressor stator position sensor that will be used on the ICLS engine. Procurement lead times necessitated ordering this sensor before the compressor actuation linkage design was begun. The recent coordination effort has involved the integration of the selection 3.8-inch stroke transducer into the linkage system. This work is proceeding and will be complete in October.

The method has been defined for utilizing engine test thermocouple signals from the HP turbine discharge (T42) and from casing involved in clearance control in the control system. The demonstrator engines will have seven T42 sensing rakes with thermocouples at five radial locations on each rake. Five of these thermocouples, one from each radial location and each from a different circumferential location, will be used exclusively by the control system. Signals from these five thermocouples will be connected in parallel in test instrumentation and the paralleled signal transmitted to the digital control.

Demonstrator engine test instrumentation will also include skin thermocouples on each of the three casings (aft compressor, HP, and LP turbine) involved in clearance control. Three thermocouples at each location will be reserved for control input sensing and will be led out to a junction box where one signal will be connected to output terminals leading to the digital control, and the other two signals will be available for control use if the other signal fails.

#### Work Planned

- No further work is planned.

## 2.9 NACELLE STRUCTURES

### 2.9.1 Nacelle Aero Design

#### Technical Progress

Final analysis and prediction of the ICLS exhaust system pressure losses were initiated. Detailed losses are being determined from the design release hardware drawings. Results will be used to update the ICLS cycle deck and engine performance projections.

The ICLS Nacelle DDR was presented at NASA-Lewis on July 9; formal approval was given to GE on July 15. A descriptive writeup for the DDR was subsequently completed.

As a result of an effort to reduce the ICLS overall engine instrumentation cost, the actual number of static pressure taps installed in the aero-acoustic inlet has been reduced to 12 pressures located in the throat region. These pressures will provide a cursory check of the wall Mach number distribution and will retain the ability to calculate inlet airflow. Provision for all originally specified 58 pressures will be made in the inlet for installation at a future date, should the need arise.

Results from the Phase III scale-model mixer test, WBS 2.6.4, were analyzed to provide final ICLS nozzle exit coefficients and estimates for the FPS nozzle coefficients. The FPS nozzle is a converging-diverging design intended to provide a desired flow coefficient characteristic between take-off and cruise. The model test indicated that the flow coefficient effect was achieved but the nozzle velocity coefficient was 1/4% below goal levels. The data analysis therefore included a trade study to obtain higher nozzle performance at the expense of desired flow coefficient trends. This information will be used in a cycle study to determine the optimum FPS nozzle configuration.

The WBS replan was completed during this reporting period.

#### Work Planned

The ICLS exhaust system pressure loss predictions will be completed; the FPS losses will also be updated. FPS nozzle exit coefficients will be finalized.

2.9  
NACELLE  
STRUCTURES

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ICLS  
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CORE  
ICLS TEST  
FPS  
CORE TEST  
ICLS TEST  
POST TEST

ACQUSTIC PANEL DESIGN  
PRELIM MECH DESIGN  
FLIGHT ENGINE COMPOSITE NACELLE MECHANICAL DESIGN  
ICLS NACELLE MECHANICAL DESIGN  
ICLS NACELLE TOOLING  
DATES SHOWN + 8 WEEKS  
ASSY & INSTRU  
ICLS TEST  
POST TEST

PRELIMINARY AERO DESIGN  
FLIGHT ENGINE COMPOSITE NACELLE AERO DESIGN  
ICLS NACELLE FABRICATION  
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DECISION DATE  
PRELIMINARY DESIGN REVIEW  
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## 2.9.2 Nacelle Mechanical Design

### Technical Progress

The objectives of this task is to design and analyze boilerplate nacelle hardware for the ICSL engine test. The basic hardware to be designed includes the inlet, outer cowl doors, core cowl doors, fan nozzle, and pylon sidewalls.

The structure for the outer cowl doors, core cowl doors, fan nozzle, and pylon sidewall was basically defined in the previous semiannual report, and a drawing of each respective component was shown. The inlet was reported earlier. The layout drawings of all the ICLS nacelle hardware have now been completed and instrumentation requirements have been incorporated into the design.

The following is a list of instrumentation items that were incorporated into each respective component of the ICLS nacelle.

#### Inlet

- 46 wall static pressure taps
- 1 T2 sensor
- 2 acoustic pressure transducers
- 3 linear potentiometers

#### Core Cowl Doors

- 1 radial  $P_T/T_T$  rake
- 13 wall static pressure taps
- 12 skin thermocouples (undercowl)
- Aft sump pressurization lead (as idle)
- Instrumentation bundle (routed through coverplates for fifth stage and CDP piping)
- Y fitting for shop cooling air/argon for fire protection

#### Outer Cowl Doors

- 1 T25 hydromechanical sensor
- 7 wall static pressure taps
- 1 acoustic traverse probe
- 7  $P_T/T_T$  arc/radial rakes

#### Fan Nozzle

- 6 wall static pressure taps
- 1 acoustic traverse probe
- 10 skin thermocouples secured on surface
- Provisions for supporting instrumentation strut.

Drawing 4013267-999 defines the positioning of the above instrumentation items which were incorporated into the nacelle design.

The ICLS nacelle DDR was presented at NASA-Lewis on July 9, 1981. Written approval of the design was received on July 24, 1981 granting authorization to proceed with the fabrication and procurement of the hardware under WBS 2.9.4.

#### Work Planned

Design support will be provided for the fabrication effort and procurement of the ICLS nacelle components to be conducted under WBS 2.9.4.

#### 2.9.4 Nacelle Hardware

##### Technical Progress

The objectives of this task are to perform the detail design of the boilerplate ICLS nacelle, fabricate the components of the ICLS nacelle, and perform a trial assembly of the components of the nacelle for the ICLS engine test. The basic hardware to be fabricated includes the inlet, outer fan cowl doors (forward fan cowl) and outer apron, inner core cowl doors and inner

apron, pylon sidewalls, active clearance control scoop and plenum for HPT and LPT, and fan exhaust nozzle (midfan cowl, aft fan cowl, and two exhaust nozzles).

#### Drawings Issued

A total of 67 detail drawings of the ICLS nacelle have been completed and issued to date which corresponds to approximately 95% of the total number of drawings to be issued.

The status of the nacelle program in general is as follows:

- Fabrication of the performance and survey nozzles has been completed
- Fabrication of the aft fan cowl has been completed
- Fabrication of the midfan cowl is 40% complete
- The core cowl door tooling is 95% complete
- 80% of the materials required to fabricate the components of the ICLS nacelle have been received
- All tools and materials are available to build the inlet assembly (bellmouth lip and diffuser)
- The quality plan for the E<sup>3</sup> nacelle program has been released
- Process planning sheets for all the major components of the nacelle (except the core cowl doors) have been completed
- Instrumentation requirements for the ICLS nacelle are currently being incorporated into the detail drawings.

#### Work Planned

- The ICLS instrumentation requirements will be incorporated into the nacelle detail drawings and the nacelle detail drawings will be completed and issued
- The fabrication of all ICLS nacelle components will be completed with a scheduled delivery date of April 1, 1982. A trial assembly of the components of the ICLS nacelle will be performed before the parts are shipped.

### 3.0 TASK 3 - CORE TESTING

#### Overall Objectives

- Design, fabricate, assemble, and test a core engine and obtain experimental evaluation of E<sup>3</sup> components operating as a system
- Develop methods by which performance of the core can be measured as to its suitability as a core for the projected Flight Propulsion System
- Evaluate performance and mechanical integrity of the core to identify changes required to meet program goals. Within program timing from cost constraints, incorporate design improvements identified from component and core testing into core and ICLS hardware.

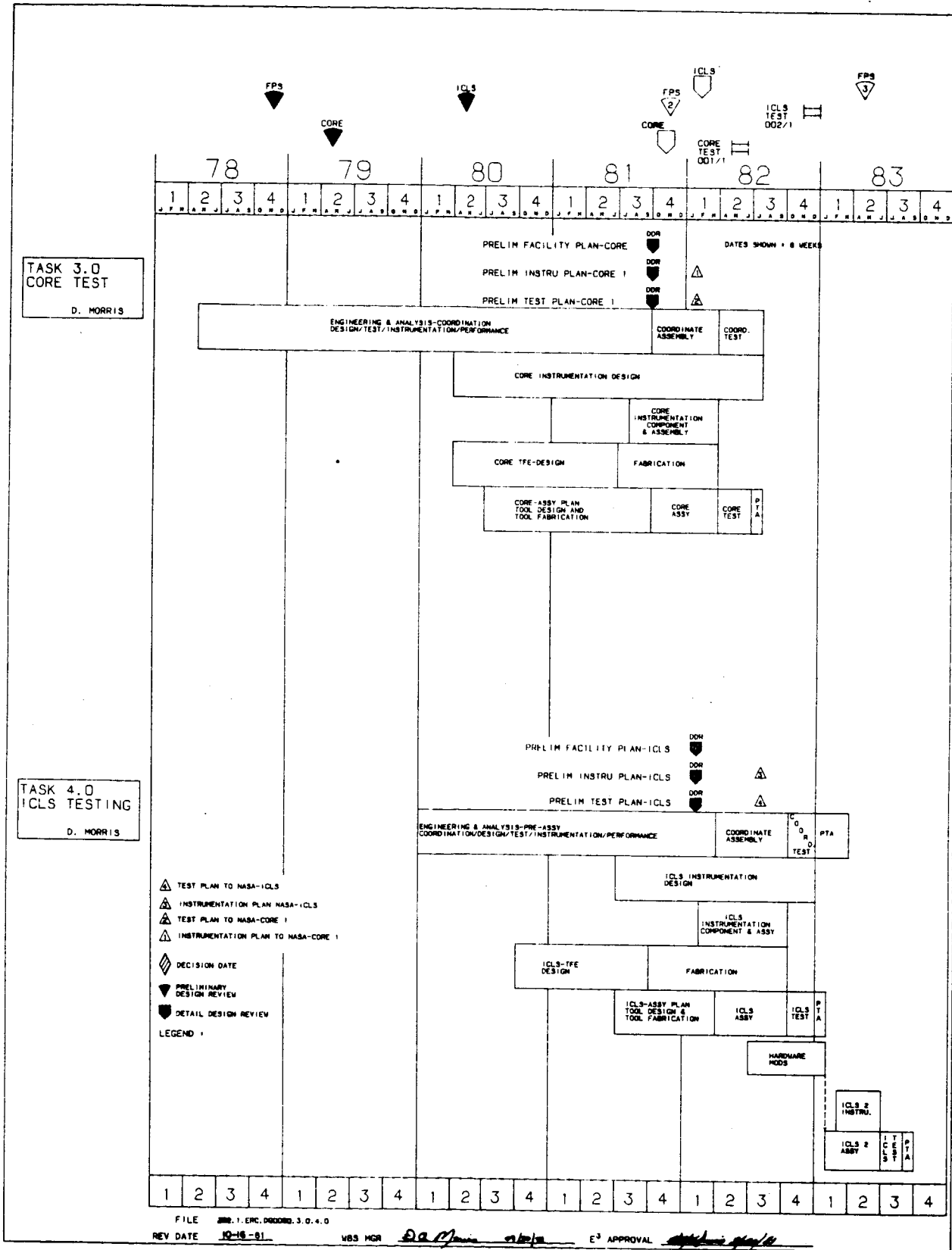
#### Development Approach (Reference WBS Spread/Schedule Sheet)

The core engine will incorporate the individual components designed and tested in part or full scale in Task 2 (Component Analysis, Design and Development). These components will include the high-pressure compressor, the combustor, and the high-pressure turbine, including clearance control devices and a control system adequate to permit starting, steady-state operation, and slow transients. The purpose of the core test will be to evaluate the performance, stability, and mechanical integrity of the components running together as a system, and to identify desirable changes for their incorporation into the ICLS or the Flight Propulsion System.

The core test vehicle will be assembled with extensive performance and mechanical instrumentation, including:

- Gas path steady-state total temperature and pressure rakes at compressor inlet, compressor exit, and turbine exit
- Rotor mechanical speed measurement
- Fuel flow measurement
- Compressor rotor and stator strain gage instrumentation based on FSCT results sufficient to monitor mechanical integrity
- Turbine rotor and stator strain gage instrumentation sufficient to monitor mechanical integrity

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- Inlet airflow instrumentation
- Variable Guide Vane setting readout
- Measurement of compressor rotor tip clearances for Stages 3, 5, and 10
- Compressor interstage steady-state instrumentation; incorporated, as necessary, to determine compressor interstage conditions
- Measurement of HPT rotor tip clearances
- Parasitic flowpath instrumentation, included to help evaluate the design of sump venting and cooling systems, and to establish the levels of parasitic flows under actual operating conditions; direct measurement of parasitic flows will be done wherever such measurements are practical in the hardware configuration
- Temperature measurements of the compressor and turbine casings for evaluation of active clearance control effectiveness
- Temperature measurements of HPT rotor, stator, and other hot structures.

The core vehicle test program will be designed to exercise the components over a sufficiently wide range to cover operating requirements in the ICLS. This will include operation at SLS ambient inlet conditions and with inlet heat/ram operation. In addition to covering the ICLS operating range, the characteristics of the core engine will be explored up to the levels of corrected airflow (120 pps) required for Flight Propulsion System operation throughout its flight envelope. This will provide an important part of the basis for extrapolating ICLS performance to altitude conditions outside the range of ICLS testing.

Prior to testing, a Core engine computer model will be constructed on the basis of component rig tests and core engine configuration assembly measurements. This model will represent the anticipated performance of the core engine and will be used in the generation of pretest predictions and in the analysis of test results.

Using the core engine computer model as a base, a data reduction program will be developed to analyze the measurements during testing. This will ensure consistency of calculation procedures between the core engine computer

model and the data reduction program, and substantially facilitate the construction of a Status Performance model.

As the engine test results are obtained, the performance of the individual components and the overall core system will be compared to the performance of the pretest prediction model. Deviations in performance will be identified and reasons for those deviations will be determined. As a result of this analysis, desirable changes will be identified for incorporation in the ICLS or the Flight Propulsion System design.

(U) At the conclusion of the core test, a Core Test Status performance computer model will be established. This will be used to project ICLS performance on the basis of the core engine demonstrated performance. In conjunction with the ICLS test results plus projected improvements anticipated from further component development, it will provide the essential basis for Flight Propulsion System performance projections.

### 3.1.1 Core Engineering and Analysis

#### Technical Progress

The primary activity during the reporting period continued to be the coordination effort between Design Engineering and the contributing support organizations (Instrumentation Design, Test Facility Engineering, and Development Assembly. The work effort was concentrated in the following areas:

- Refinement to the instrumentation and assembly plans
- Refinement of the assembly schedule
- Providing hardware rework definition for instrumentation, application, and lead routing
- Definition of assembly - level machining operations for proper engine clearances
- Monitor tooling design for rotor balance and assembly machining
- Continue work on subassembly buildup procedures
- Follow activities for instrumentation design, facility hardware design, and assembly tooling.

- Monitoring hardware design for assembly and maintainability considerations
- Hold design reviews for compressor instrumentation and test facility hardware

#### Work Planned

- Continue to monitor the progress of assembly buildup procedures, tooling design, and procurement
- Complete the detailed design for instrumentation application
- Begin the application of instrumentation to engine hardware
- Initiate the centerline shell stack and grinding of bearing housings
- Begin core assembly
- Continue the design of remaining test facilities hardware and follow hardware procurement.
- Continue to provide coordination between Design Engineering and the contributing support organizations
- Develop the final test plan
- Complete the core overall instrumentation list and drawing.

### 3.1.2 Core Instrumentation and Assembly

#### 3.1.2.1 Instrumentation Design

#### Technical Progress

The major work effort during the past 6 months was in defining methods for the application and leadout of instrumentation sensors and the corresponding vehicle hardware rework requirements. The major activities were:

- Completed design of the compressor discharge (Plane 3.1) total pressure and total temperature rakes and initiated manufacture
- Defined hardware rework required to install and leadout sensors for aerodynamic and mechanical data for the compressor rotor, compressor stator, combustor-diffuser high pressure nozzle, turbine rotor, turbine stator, and rear frame subassemblies

- Provide conceptual designs of the forward and aft sliprings; Initiated detail drawings to manufacture hardware
- Completed preliminary designs of the turbine discharge (Plane 4.2) total pressure and total temperature rakes
- Initiated design of the compressor clearance measurement systems for Stages 3, 5, and 10
- Initiated fabrication of the compressor rotor instrumentation lead-out duct
- Placed an order for all the required vehicle accelerometers
- Initiated application drawings for the compressor and turbine rotors.

#### Work Planned

- Finalize all hardware rework definition
- Complete all subassembly and main engine level application drawings
- Initiate fabrication of all rakes.

#### 3.1.2.2 Instrumentation Application

##### Technical Progress

- Initiated the thin-film process for applying strain gages on the Stages 1-7 compressor rotor blades and IGV through Stage 6 stator vanes
- Began the fabrication of the individual aerodynamic sensors for vane-mounted compressor stator measurement of total pressure and total temperature.

#### Work Planned

Initiate instrumentation application of vehicle hardware as the parts became available.

#### 3.1.2.3 Core Assembly

##### Technical Progress

During this reporting period, most of the work efforts were associated with providing written subassembly buildup procedures, designing assembly

tooling, and initiating fabrication of the tooling. Some early vehicle assembly activities were also initiated. The major efforts were:

- Completed design of all known assembly and balance tooling
- All balance and assembly tooling required for the initial buildup activities has been procured
- Completed the written buildup procedures for the compressor rotor, forward sump/inlet gearbox, CDN, and Stage 2 nozzle sub-assemblies; work is progressing on the remaining subassemblies
- Initiated buildup of the compressor rotor; check-balanced the 6-10 spool, Stage 5 disk, and CDP seal disks; trial-fitted Stage 5-7 rotor blades.

#### Work Planned

- Complete the remaining assembly procedures and procure the remaining tooling
- Initiate vehicle assembly activities as the hardware becomes available.

#### 3.1.2.4 Signal Conditioning

##### Technical Progress

- Assembly of the laser clearance probe electronics and optics is underway; all detector circuits are assembled, epoxy potted, and tested; lens holder fabrication is started; some vendor supplied parts remain to be delivered.
- The "dummy" probes are being manufactured
- The existing CDP air cooling cart should be suitable for use on the core engine.

##### Work Planned

Complete fabrication of the probes and complete the manufacture of the "dummy" blackoff probes.

### 3.1.3 Core Test Facilities Engineering

#### Technical Progress

Completed the design of the slave stator actuation system, the cell inlet and ram air supply ducting, including pre- and main-filter elements which mount in common design casings. Definition of slave service requirements was completed. Completed design for air supply to the two starters.

Progress was made on the cell layout for engine installation. The buildup/transport dolly is nearing design completion. A greatly simplified design for the turbine clearance control air manifolds was developed.

A layout of the control room was outlined for locating FADEC hardware and sizing cables to the engine. Throttle handle modifications were also outlined for PLA input to the FADEC and F101 hydromechanical controls (including reduction drive capability).

#### Work Planned

- Complete engine installation definition with details of manifolds connecting overhead piping and mounted to the transport dolly
- Complete details of exhaust system design
- Purchase all engine installation hardware
- Review optical clearance probe cooling supply hardware design and modifications, and locate equipment space near and adjacent to cell.

#### 4.0 TASK 4 - ICLS TESTING

##### Overall Objectives

- Design, fabricate, assemble, and test a turbofan demonstrator engine and obtain experimental evaluation of E<sup>3</sup> components operating as a system
- Develop methods by which performance of the turbofan demonstrator engine can be measured as to its suitability toward the projected Flight Propulsion System
- Evaluate performance and mechanical integrity of the turbofan demonstrator engine to identify changes required to meet program goals.

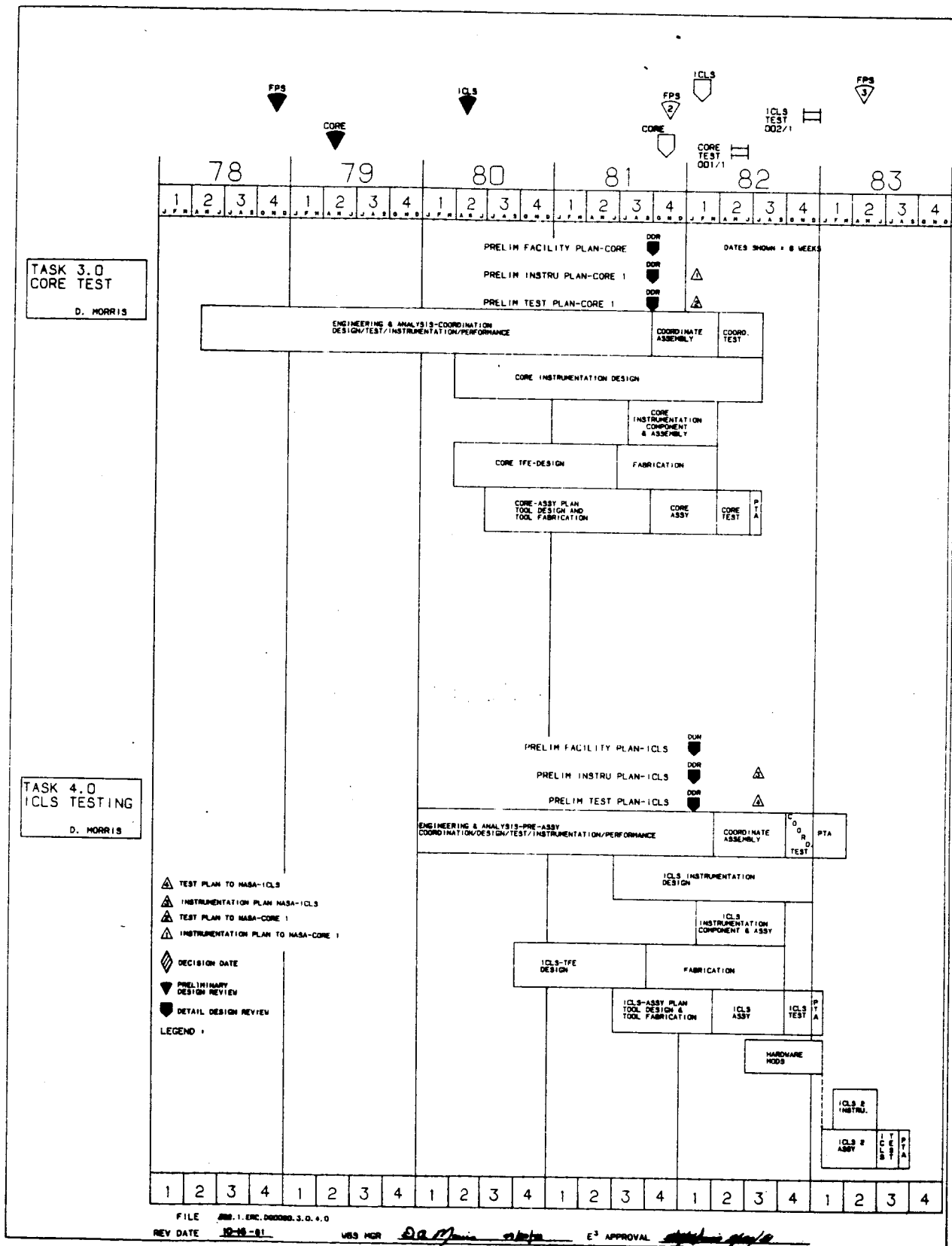
##### Development Approach (Reference WBS Spread/Schedule Sheet)

The turbofan engine will incorporate the individual components designed and tested in part or full scale in Task 2 (Component Analysis, Design, and Development). These components will include the high-pressure compressor, combustor, high-pressure turbine, fan, low-pressure turbine, and mixer including clearance control devices and a control system adequate to permit starting, steady-state operation, and slow transients. The current plan is to use the applicable core test vehicle and full-scale fan test vehicle component hardware in the assembly of ICLS. This assumes that there will be no major hardware modifications required as a result of the individual component tests. The purpose of the ICLS test will be to evaluate the performance, stability, and mechanical integrity of the components running together as a system, and to identify desirable changes for the Flight Propulsion System.

The turbofan test engine will be assembled with extensive performance and mechanical instrumentation, including:

- Gas path steady-state total temperature and pressure rakes at the fan inlet, compressor inlet, compressor exit, HP turbine exit, LP turbine exit, and mixer exhaust.
- Rotor mechanical speed measurements
- Fuel flow measurement

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- Fan rotor and stator strain gage instrumentation based on FSFT results sufficient to monitor mechanical integrity
- Low pressure turbine rotor and stator strain gage instrumentation sufficient to monitor mechanical integrity
- Inlet airflow instrumentation
- Variable Guide Vane setting readout
- Combustor static pressure (control pressure) measurement
- Compressor interstage static pressure instrumentation; incorporated, as necessary, to determine compressor interstage conditions
- Direct measurement of HPT rotor tip clearances
- Parasitic flowpath instrumentation, included to help evaluate the design of sump venting and cooling system, and to establish the levels of parasitic flows under actual operating conditions; direct measurement of parasitic flows will be done wherever such measurements are practical in the hardware configuration
- Measurements of baseline and fully suppressed acoustical characteristics
- Exhaust emissions measurement
- Temperature measurement of the compressor, HPT, and LPT cases sufficient to evaluate active clearance control effectiveness
- Temperature measurements of LPT rotor, and other bolt structures.

The ICLS test program will be designed to test the components over the entire range of ICLS operating conditions. All testing will be at ambient inlet conditions. In addition to covering the ICLS operating range, the characteristics of the core engine will be explored up to the levels of corrected airflow (120 pps) required for Flight Propulsion System operation throughout its flight envelope. This will provide an important part of the basis for extrapolating ICLS performance to altitude conditions outside the range of ICLS testing.

Prior to testing, an ICLS computer model will be constructed on the basis of component rig tests, core engine test, and the ICLS configuration assembly measurements. This model will represent the anticipated performance

of the ICLS engine and will be used in the generation of pretest predictions and in the analysis of test results.

Using the ICLS computer model as a base, a data reduction program will be developed to analyze the measurements during testing. This will ensure consistency of calculation procedures between the ICLS computer model and the data reduction program, and substantially facilitate the construction of a Status Performance model.

As the engine test results are obtained, the performance of the individual components and the overall engine system will be compared to the performance of the pretest prediction model. Deviations in performance will be identified and reasons for those deviations will be determined. As a result of this analysis, desirable changes will be identified for the Flight Propulsion System design.

#### 4.1.1 ICLS Preassembly Engineering and Analysis

##### Technical Progress

During this reporting period, the primary task continued to be the definition and engineering coordination effort between Design Engineering and the contributing support organizations. The majority of the work effort was in the following areas:

- Definition of preliminary assembly, instrumentation, and test facility plans
- Completed design of ICLS mount system
- Completed preliminary instrumentation drawing
- Monitored progress of the full-scale fan test vehicle hardware and instrumentation designs to assure compatibility with ICLS
- Monitored hardware design for assembly, maintainability, and installation considerations
- Provided hardware rework definition for the application and leadout of instrumentation on the LP turbine and nacelle
- Definition and documentation of engine to facility interfaces

- Definition of LP turbine rotor balance and assembly procedures
- Definition of in-assembly machining procedures required to maintain engine clearances.

#### Work Planned

Continue with the coordination and definition effort between Design Engineering and the support organizations. Initiate instrumentation design for the fan and LP turbine subassemblies. Continue to refine the assembly and instrumentation plan. Define cowling rework for instrumentation application. Define main engine level installation of LP turbine module procedure. Initiate assembly written procedures and tooling design.

#### 4.2.2.1 LPT Rotor Hardware (for ICLS Test)

##### Technical Progress

All rotor hardware has been placed on order and a large portion of the rotor machining has been completed. Several completed parts have been received. All scheduled part deliveries meet the dates required for ICLS buildup.

##### Blades

Details on the blades are reported under WBS 2.5.6.1.

##### Rotor

During this reporting period, all five stages of the low pressure turbine disks have been contour machined and have had their dovetail slots machined by wire EDM. The disks are now in different stages of the final machining operations which consist of machining the boltholes, cutting the scallops in the flanges, and turning the outside diameter.

Shot peening of the entire surface of the low pressure turbine disks was defined per discussions with Materials and Manufacturing Engineering. Also, the shot peening intensity in the EDM'ed dovetail slots was revised to a more intense peening based on E<sup>3</sup> high pressure turbine test results.

The Stage 1, 4, and 5 rotor seals have been finished and shipped to General Electric.

The Stage 2 rotor seal was machined by the vendor; the aft surface of the seal that rests against the disk was machined 0.030-inch undersize. Dabber welding was used to repair the seal. It is a miniature TIG weld that has been used successfully in the past to repair rotor seal teeth. It was chosen because of its ability to build up thin parts and because it was not expected to warp the part significantly. The seal was dabber welded at General Electric, heat treated, then sent back to the vendor for final machining. The weld area "cleaned up" and distortion of the vertical arm due to welding was found to be negligible.

The Stage 3 rotor seal was also mismachined because the part position shifted during manufacturing. The thickness of the flange was cut under minimum and therefore could not be accepted. A new forging was supplied to the vendor for remachining and it is now nearing completion. The finished part is expected to be shipped in early October.

Rework for instrumentation is required on Stage 1 and 2 rotor seals and Stage 1-4 disks. Two methods were considered for routing leads from the blades to the inside diameter of the disks. One was to machine grooves in the disk aft flange faces and to run the lead between the disk flanges and the rotor seal flanges. The other was to drill local holes through the disk arms. In both cases, the stress concentration factors were found to be approximately 3.0, however the stresses in the disk arms are less than the stresses in the disk flanges. Therefore, it was considered more desirable to drill holes through the disk arms than to machine grooves in the disk flanges. Shop modification drawings for the seal and disk rework have been completed and work authorizations for the rework have been released.

A review of the low pressure turbine assembly sequence for ICLS revealed the desirability of a locking feature to hold the rotor seals to the Stage 2 and 3 disks at assembly. After a review of several concepts, a "C" clip ring retainer design was chosen, like that already specified for the torque cone joint. These parts are on order.

### Fasteners

Rotor spool fasteners are being received ahead of schedule. Bolts for all stages have been received (8 special assembly bolts remain in process), and all nuts except those for Stage 1 have been received.

### Work Planned

- Complete final machining and shot peening of LPT disks
- Complete machining of Stages 2 and 3 rotor seals
- Complete instrumentation rework of LPT disks and seals.

### 4.2.2.2 LPT Nozzle Hardware

### Technical Progress

All hardware items for ICLS have been ordered and scheduled deliveries meet the required dates for ICLS buildup.

### Nozzles

See WBS 2.5.6.2 (for Stage 1) and WBS 2.5.6.3 (for Stages 2 through 5).

### Forward Inner Seal Support

The forward inner seal support has been completed and is in engineering stores awaiting instrumentation rework definition. Due to a concern over possible distortion of the support, the sinter process was removed from the wear coat which is applied to several support surfaces. The purpose of the sinter process was to provide a harder, more durable wear coat, but the wear resistance is still considered more than adequate for ICLS testing without the sintering.

Instrumentation requirements have been identified and initial rework definition has been laid out. Instrumentation rework drawings will be issued and the part modified.

The honeycomb seal final diameter will be delineated on the Stage 1 nozzle subassembly drawing and will be ground at assembly.

### Aft Inner Seal Support

The aft inner seal support has been completed and is awaiting a fixture for flow check. As with the forward inner seal support, the sinter process was removed from the wear coat.

Instrumentation rework is now being defined. Rework drawings will be issued and rework completed after flow check testing.

### Work Planned

- Issue instrumentation rework drawings for forward and aft inner seal supports
- Issue Stage 1 nozzle subassembly drawings with final honeycomb seal diameters defined
- Provide engineering support of hardware through manufacturing
- Trial fit all available hardware
- Flow check aft inner seal support and Stage 1 nozzle.

### 4.2.2.3 LPT Static Structures Fabrication

#### Technical Progress

All hardware items for ICLS have been ordered and scheduled deliveries meet the required dates for ICLS buildup.

### LPT Casing

Fabrication of the LPT casing has continued. Rough machining of the separate forward and aft forging shells was completed in April. The two shells were EB welded and heat treated prior to final machining in May. Templates for the OD and ID machining were obtained and the OD machining was completed in August. The ID machining is currently in process, to be followed by flange and boss machining in September.

A decision was made in July to increase the shell thickness approximately 0.020 to add stability to the LPT casing during machining. This is to reduce the risk of scrapping this one-of-a-kind ICLS case.

All existing drawing changes (DCID's) have been issued and incorporated into the LPT casing manufacture. This includes incorporation of the instrumentation bosses into the integral forged material - thus eliminating later addition instrumentation rework.

#### Outer Duct Support

The outer duct support is nearly complete; however, resolution of two manufacturing discrepancies has delayed completion. Instrumentation rework drawings are nearing completion, and the rework will be incorporated in manufacturing.

A design change was made to the flex arm region so that a splash shield could be included in the assembly without interference (see WBS 2.5.3.3.).

#### Miscellaneous Hardware

All miscellaneous hardware is on order and delivery dates are on or before March 1982.

#### LPT Cooling/Active Clearance Control Impingement Manifold

Orders for all the LPT cooling manifold and its mounting hardware were placed during this report period. Fabrication of the cooling manifold hardware continued with cost and delivery dates unchanged during this report period. All nut fasteners have been received, ahead of schedule.

#### Work Planned

- Continue fabrication of the LPT casing
- Continue to monitor manifold hardware ordered
- Complete manufacture of outer duct support including instrumentation rework
- Trial fit all available hardware.

#### 4.2.2.4 LPT Shroud (and Seals) Hardware

##### Technical Progress

All hardware items for ICLS have been ordered and scheduled deliveries meet the required dates for ICLS buildup.

##### Shrouds Stage 1 Through 5

All five stages of the E<sup>3</sup> LPT honeycomb shrouds were placed on order during this report period. A temporary hold on manufacturing was implemented because dimensional changes were required to relieve anticipated assembly problems identified in studies of assembly procedures.

The DCID necessary to release all five stages of the E<sup>3</sup> LPT shroud from the manufacturing "HOLD" has been completed, issued, and is in the process of being coordinated with the vendor. The established delivery date may be affected, but should fall within the required delivery date to meet the ICLS assembly requirements.

All insulation blankets for the E<sup>3</sup> LPT were placed on order during this report period. This included the insulation blanket over the Stage 1 nozzle as well as the other LPT insulation blankets identified at the start of this report period. These other blankets are for locations at the inner and outer transition duct between the HPT and LPT, over all five stages of the LPT shrouds, and over the nozzles in Stages 2 through 5. Some discrepancies exist between the drawings and the vendor's manufacturing techniques. A DCID has been started to make the drawing compatible with the manufacturing techniques.

The quoted ship dates for all the LPT insulation blankets are well within the required data for ICLS assembly.

##### Transition Ducts

One engine set of inner and outer duct castings is now available to start machining. The balance of the order will be supplied in October 1981. Photographs of sample wax patterns are shown in Figure 4.2-1. Instrumentation rework has been defined and incorporated into the planning for transient duct

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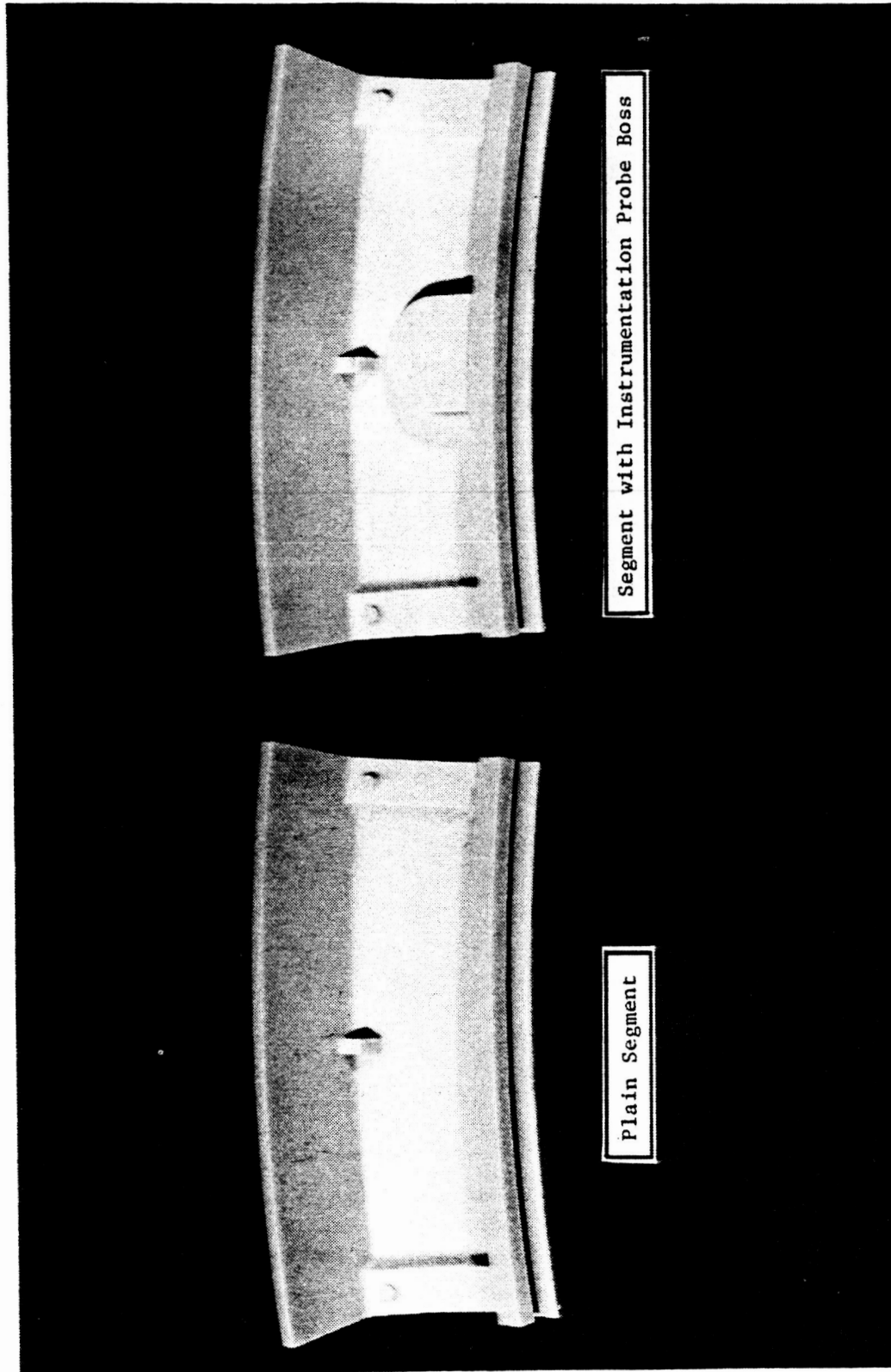


Figure 4.2-1. Outer Transition Duct Segments, Sample Wax Patterns.

machinings. A DCID was recently issued which changes the duct machining drawings, reducing the seal slot depths for ease of manufacture and a reduction in cost. These changes have also been incorporated into planning for the machining.

### Strip Seals

Design changes incorporated into the duct and nozzle machinings, which reduced seal slot depths, required a corresponding change to the spline and hourglass strip seal drawings. A DCID was issued which reduced the seal widths on the appropriate detail drawings and also created parts made of Kanthal<sup>®</sup> material. A sufficient quantity of parts made of Kanthal<sup>®</sup> as well as Hastelloy X have been ordered to assemble the ICLS engine with one half set of each for evaluation. The Kanthal<sup>®</sup> offers potential improvements in oxidation resistance and flexibility after long time exposure.

### Work Planned

- Provide engineering support of hardware through manufacturing and instrumentation
- Trail fit all available hardware
- Issue instrumentation rework drawings
- Coordinate incorporation of the shroud DCID with the vendor
- Complete and issue DCID for insulation blanket
- Continue to monitor ordered hardware.

### 4.2.3 Bearings, Systems, Drives, and Configuration Fabrications

#### Technical Progress

All hardware for the ICLS sumps and drive system is on order. A meeting was held with the LPT shaft vendor to review engineering intent and manufacturing processes, and no basic problems were encountered.

Configuration hardware required for the ICLS engine is scheduled for release for manufacturing during the next reporting period and detail drawings are being issued to meet this schedule.

Quotes received on the pressure bulkhead were higher than anticipated and Purchasing and Engineering are working with vendors to reduce cost.

#### Work Planned

- Continue procurement of ICLS hardware.

#### 4.3.1 ICLS Instrumentation Design

##### Technical Progress

All the work activity during this reporting period was associated with providing preliminary definition of hardware modifications required for sensor application and leadout.

- Defined frame rework required to mount the LP turbine discharge (Plane 5) total pressure and total temperature rakes
- Defined rework to the LP turbine case and nozzle hardware
- Initiated design of the exhaust plane survey aerodynamic rake and traversing system
- Provided a conceptual plan for measuring the relative motion between the fan inlet and the fan frame
- Began working with Design to identify application and leadout on the LP turbine stator.

#### Work Planned

- Continue to provide hardware modification definition as required by Design Engineering
- Begin detail design of fan and LP turbine application drawings.

#### 4.4 ICLS TEST FACILITIES ENGINEERING

##### Technical Progress

- Completed facility mount design and placed the mount hardware on order
- Completed "dummy" engine design and initiated fabrication

- Reviewed design of the inlet, fan, and core cowling with Evaluation and Design and defined all interface points between TFE and engine hardware.

#### Work Planned

- Complete design of inlet support tooling for bellmouth and acoustic inlet
- Start installation concept drawing showing ICLS on Site IV-D test stand
- Firm up design requirements on all slave systems
- Prepare proposal defining all facilities required, their cost, and timing.

## EXHIBIT B

### TECHNICAL PROGRESS

During this period, the following has been accomplished:

- Monitored the testing of the Stage 1-10 Compressor, and then, pursuant to the termination of testing on April 10, coordinated the return to Evendale and rig teardown with Development Assembly Quality. Maintained continued communication with NASA Product Assurance throughout failure investigation and issuance of the Engine Damage Report.
- Initiated a procedure to upgrade catalog type hardware procured directly by E<sup>3</sup> Engineering to Class "N" as required by contract. In this instance, Specification Control Drawings ("typewriter" drawings) are used to assign a GE part number to a specific catalog item and thereby permit configuration/quality control.
- Coordinated the assembly of the fan test rig with Development Assembly Quality and the shipment/receipt with Lynn Component Test Quality.
- Participated in component and rig test design reviews, and program and hardware reviews during the reporting period.
- Coordinated the continued review of quality plans and the procurement of selected inspection data.

### WORK PLANNED

- Closely follow the hardware procurement and the assembly of the Phase II Stage 1-10 Compressor Rig and the shipment to/and testing at Lynn.
- Follow-up on the task of upgrading catalog hardware to Class "N".
- Continue to monitor and review all aspects of the program participating in program and design reviews to ensure compliance with the Quality Assurance Program Plan. Also, maintain close contact with E<sup>3</sup> Engineering to assist in the expediting of hardware while maintaining the required quality control discipline.
- Maintain continued interface with NASA Product Assurance Manager and designated AFPRO offices at Evendale.